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Mangrove Ecosystem Quality Index: Combining Field-Based Vegetation Structure and Water Quality to Assess Mangrove Ecosystem Condition in Segara Anakan, Cilacap, Indonesia

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Abstract

Comprehensive mangrove health assessments require evaluating both historical vegetation structure and dynamic water quality, yet these domains are rarely integrated into a single field-based index. This study develops the Mangrove Ecosystem Quality Index (MEQI) to address this gap, applying it to 45 sampling points in the Segara Anakan lagoon, Indonesia. The MEQI combines a Vegetation Structure Index (ISV) and a Water Quality Index (IWQ), each comprising six parameters weighted empirically through principal component analysis (PCA). Point-level scores were mapped utilizing inverse distance weighting on a hexagonal grid. Results indicate an average MEQI of 51.76, with 2 stations classified as Very Good, 26 as Good, 15 as Moderate, and 2 as Poor. Spatially, ecosystem health was strongest in the north-central and western sectors but degraded along the eastern arm due to anthropogenic loads. Notably, evaluating the sub-indices independently revealed a statistically significant divergence: vegetation structure (average ISV 40.77) was substantially more degraded than water quality (average IWQ 62.75). Relying solely on the composite MEQI risks a masking effect, where functional aquatic conditions obscure historically degraded vegetation. The PCA weights highlighted carbon stock, biomass, pH, and dissolved oxygen as primary ecosystem drivers. The MEQI serves as a practical, field-deployable tool that robustly complements remote-sensing approaches like the Mangrove Ecosystem Health Index (MEHI). For effective conservation, managers must utilize such integrated indices to periodically monitor the disparate recovery timelines of structural and aquatic mangrove dimensions.

Highlights

- A field-deployable index (MEQI) combines vegetation structure and water quality at 45 points.
- PCA empirically weights six vegetation and six water-quality parameters rather than a priori weighting.
- Applied to the Segara Anakan lagoon, Cilacap, Indonesia; MEQI averaged 51.76 (range 23.30-76.19).
- Vegetation structure, not water quality, is the main constraint on ecosystem condition lagoon-wide.
- Hexagonal-grid IDW mapping flags the eastern arm of the lagoon as a rehabilitation priority.

1. Introduction

Mangrove forests occupy the intertidal boundary between land and sea across tropical and subtropical coastlines, where they provide coastal protection, high rates of carbon storage relative to other forest types, and nursery habitat that supports much of the region's coastal fisheries (Alongi, 2002, 2014; Barbier et al., 2011; Donato et al., 2011). Despite this recognized value, global mangrove area has continued to decline, driven principally by conversion to aquaculture, coastal development, and pollution (Duke et al., 2007; Friess et al., 2019; Giri et al., 2011; Polidoro et al., 2010). This decline has motivated growing investment in mangrove restoration, together with calls for monitoring tools capable of tracking conditions consistently across sites and over time (Friess et al., 2019). In practice, however, most monitoring approaches remain confined to one of two domains: forest-structural assessment,

conducted through field inventory or remote sensing, or water-quality assessment, conducted through in-situ or laboratory analysis of tidal creek water; the two are rarely combined within a single index. This separation is significant because the two domains operate on different temporal scales. Vegetation structure reflects the cumulative outcome of growth and disturbance over years to decades, whereas water quality can change within a season, or within days, in response to tidal exchange, rainfall, and discharge from surrounding land use (Lonergan et al., 2026; Pradit et al., 2026), a pattern documented directly for mangrove-adjacent waters by multi-index water-quality assessments in Vietnam (Nguyen et al., 2026) and by a 28-year urbanization record in Brazil showing that mangrove forests buffer adjacent waters against urbanization-driven eutrophication (Rodrigues et al., 2026).

Recent evidence illustrates the practical consequence of this mismatch. Planted mangroves can achieve high survival and canopy cover within a few years, while the underlying sediment biogeochemical processes that govern contaminant retention and nutrient buffering may require decades to converge toward the condition of mature natural stands (Pradit et al., 2026). Conversely, water-quality-relevant nutrient fluxes can shift substantially following a single restoration intervention, independent of any corresponding change in forest structure (Lonergan et al., 2026). Assessing mangrove condition from either domain in isolation therefore risks an incomplete or misleading characterization, particularly when comparing young, restored stands against mature natural forest.

The general approach of combining multiple environmental measurements into a single interpretable score has a long precedent outside mangrove research. Karr (1981) introduced the Index of Biotic Integrity for freshwater fish assemblages, and (Brown et al., 1970; Brown & McClelland, 1974) introduced the water quality index framework that converts multiple physicochemical parameters into standardized sub-index scores before combining them arithmetically. Several composite indices adapt this logic specifically to mangroves. The Mangrove Quality Index integrates biotic, soil, marine, hydrological, and socio-economic variables through principal component analysis (Faridah-Hanum et al., 2019), while the Mangrove Sediment Quality Index focuses specifically on sediment heavy-metal enrichment (Mohamad Pazi et al., 2021). At Segara Anakan, the same lagoon examined in this study, Rahmila et al. (2026) developed a landscape-scale Mangrove Ecosystem Health Index (MEHI) constructed entirely from remote-sensing data: canopy density derived from an Enhanced Mangrove Index, hexagonal-grid spatial metrics, and a disturbance index based on distance to settlements, ports, and roads. Vegetation condition has also been assessed through spectral vegetation indices more broadly, from the original Normalized Difference Vegetation Index (Rouse et al., 1974) to mangrove-specific and red-edge derivatives that can be computed without field access (Anggraeni & Setiawan, 2025; Rendana et al., 2026). Each of these approaches performs well within its intended scope but requires resources not universally available to field teams: the MQI requires socio-economic and sediment or phytoplankton laboratory data, and the remote-sensing-based approaches require GIS infrastructure and imagery-processing capacity. What remains comparatively underdeveloped is an index constructed only from measurements obtainable with a forestry tape and a portable water-quality meter, pairing vegetation structure directly with in-situ water chemistry rather than substituting one domain for the other.

This paper develops such an index, the Mangrove Ecosystem Quality Index, for the Segara Anakan lagoon. The specific objectives are to (1) measure vegetation structure and water quality at 45 sampling points spanning the lagoon's condition gradient, following the plot design specified in Indonesia's national forest inventory protocol (IHN 2.0) for the vegetation component; (2) construct a Vegetation Structure Index (ISV) and Water Quality Index (IWQ) from six parameters each, weighted empirically through principal component analysis; (3) combine the two sub-indices into a composite MEQI and classify it into ordinal condition categories; (4) map the resulting index across the lagoon through spatial interpolation on a hexagonal grid; and (5) examine what the two sub-indices reveal separately that the composite score does not, how the index relates to existing mangrove indices, and evaluate its potential application in regular conservation monitoring programs.

2. Methodology

2.1. Study Area

This study was conducted in the Segara Anakan lagoon, Cilacap Regency, Central Java, one of the largest remaining lagoon-type mangrove systems on Java (Fig. 1). The lagoon is shallow and brackish, fed by the Citanduy River and its tributaries, with salinity that varies markedly with season and tidal state (Rahmila et al., 2026). Mangrove cover consists of a mosaic of natural stands, areas dominated by Nypa fruticans, invasive-shrub-colonized understorey, and unvegetated tidal flats. Decades of sedimentation, conversion to aquaculture and settlement, agricultural runoff, and port-related activity have produced a wide range of condition across the lagoon, from severely degraded stands to relatively intact, community-conserved forest (Jennerjahn & Yuwono, 2009; Nordhaus et al., 2019; Rahmila et al., 2026). Forty-five sampling points were distributed across the mangrove-dominated area of the lagoon to represent this condition gradient.

2.2. Field Data Collection

At each of the 45 points, a vegetation plot and a water sample were taken at the same time, so every point produces one paired vegetation–water observation for the index calculation that follows.

2.2.1. Vegetation Structure

Vegetation was assessed following the nested subplot design specified for the mangrove stratum in Indonesia's national forest inventory guideline (IHN 2.0), established under Keputusan Direktur Jenderal Planologi Kehutanan Nomor 3 Tahun 2025 (Direktorat Jenderal Planologi Kehutanan, 2025). Figure 2 illustrates both the national design and the plot geometry adopted in this study. The national design arranges three plots in an L-shaped cluster (a central plot and two additional plots located 50 m to the north and east), each comprising four concentric subplots keyed to diameter class. Because this three-plot arrangement is intended for national-scale population estimation rather than site-level assessment,

each of the 45 sampling points was established as a single plot using the subplot geometry alone, consistent with the simplification adopted by Rahmila et al. (2026) in ground-truthing the same lagoon.

All live stems within each plot were identified to species and measured for diameter at breast height and total height, following the IHN 2.0 convention for the measurement point on different mangrove growth forms (Fig. 3). Stems were recorded regardless of size class, since several sectors of Segara Anakan support young, structurally simple stands for which the 5 cm diameter threshold used in the national-scale inventory would have excluded a substantial proportion of individuals.

Height was measured on at least six trees per plot, chosen to span the small, medium, and large diameter classes present, following standard mensuration practice (Husch et al., 2003). Canopy cover came from hemispherical photography, an optional method under IHN 2.0. Stand density was scaled to a per-hectare basis, and biomass and carbon stock were estimated from diameter and height with the pantropical allometric equations of Chave et al. (2014) and a species-level carbon fraction. Table 1 lists the six resulting parameters that feed the Vegetation Structure Index (ISV).

Table 1
The six vegetation parameters behind the Vegetation Structure Index (ISV).

Parameter	Measurement Method	Unit
Diameter at breast height (DBH)	Direct tape measurement / mangrove-specific convention (Fig. 3)	cm
Tree height	Total and bole height on ≥ 6 sample trees per plot (Husch et al., 2003)	m
Canopy cover	Hemispherical photography	%
Stand density	Stem count per plot, scaled to per hectare	ind. ha^{-1}
Aboveground biomass	Pantropical allometric equation (Chave et al., 2014)	kg ha^{-1}
Aboveground carbon stock	Biomass × species carbon fraction	t C ha^{-1}

2.2.2. Water Quality

Water quality was checked at the same 45 points, combining in-situ readings with laboratory analysis, in line with methods used in comparable mangrove and estuarine studies (Nguyen et al., 2026; Pradit et al., 2026; Samsudin et al., 2019; Umroh et al., 2026). pH, dissolved oxygen, and salinity were read on site with a calibrated multi-parameter meter at the time of vegetation sampling. Meanwhile, water samples were collected, preserved, and transported to basecamp under standard protocol (APHA, 2012) for determination of nitrate, ammonia, and phosphate. Together these six parameters make up the Water Quality Index (IWQ): pH, dissolved oxygen, and salinity contribute positively to the index, while nitrate, ammonia, and phosphate contribute negatively, since higher nutrient concentrations point to greater eutrophication pressure rather than better condition.

2.3. Development of the MEQI

The MEQI is constructed from the two sub-indices described above, ISV and IWQ, both measured at the same 45 points, standardized to a common 0–100 scale, weighted using principal component analysis of the field dataset, and combined into a single composite score. The resulting point-level scores were then interpolated across the lagoon and summarized on a hexagonal grid.

2.3.1. Data Standardization

$qi = 100 \times \ (xi - xmin)/(xmax - xmin)$ for positively-oriented parameters (1a)

$qi = 100 \times \ (xmax - xi)/(xmax - xmin)$ for negatively-oriented parameters (1b)

Here xi is a parameter's value at a given point, and $xmin/xmax$ are the minimum and maximum of that parameter across all 45 points. All six vegetation parameters run through Eq. 1a. On the water-quality side, pH, dissolved oxygen, and salinity also use Eq. 1a, while nitrate, ammonia, and phosphate use Eq. 1b. The result is every parameter sitting on the same 0–100 scale, regardless of its original units.

2.3.2. Weighting the Indicators

Rather than assigning indicator weights a priori, this study derived them empirically through principal component analysis of the field dataset, consistent with the approach used to construct the Mangrove Quality Index (Faridah-Hanum et al., 2019) and the sediment–water quality assessment of Umroh et al. (2026), and comparable in principle to the AHP-based weighting used by Wang et al. (2026) for their structure–function mangrove index and by Rahmila et al. (2026) for their hexagonal-grid MEHI. Principal component analysis was applied separately to the six standardized water-quality parameters and the six standardized vegetation parameters across the 45 sampling points. In each case, the first principal component was extracted, since it accounts for the largest share of variance among the six parameters within that domain. The absolute value of each parameter's loading on this component was taken as its raw weight, and raw weights were rescaled within each domain to sum to one. Sampling adequacy for applying PCA to each parameter set was assessed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity. The resulting weights, together with these diagnostic statistics and the computed IWQ, ISV, and MEQI values, are reported in Section 3.1; this section describes only the derivation procedure. Principal component analysis, the KMO and Bartlett's tests, and the IDW interpolation were all performed in R (R Core Team, 2024).

2.3.3. Combining the Sub-Indices

At each point, the weights from Section 2.3.2 were applied to the standardized parameters and summed within each domain:

$$IWQ = \Sigma \left(standardizedwater - qualityparameter \times \ itsweight\right)$$

$$ISV = \Sigma\left(standardizedvegetationparameter \times\ itsweight\right)$$

3

IWQ and ISV were then combined into the composite MEQI, giving each domain equal weight:

$$MEQI = (0.5 \times\ IWQ) + (0.5 \times\ ISV)$$

4

Since IWQ and ISV both sit on a 0–100 scale and the two domain weights sum to one, MEQI stays on that same 0–100 scale.

2.3.4. Spatial Interpolation

The values were interpolated with Inverse Distance Weighting (IDW), which estimates unsampled locations as a distance-weighted average of the nearest observed points. The interpolated surface was then laid over a hexagonal grid covering the mangrove area of Segara Anakan, the same spatial framework that Rahmila et al. (2026) used for their landscape-scale MEHI at this site, chosen because it keeps edge effects down and gives a consistent unit for comparing across the lagoon. Each hexagon's score is the mean of the interpolated surface within its boundary, taken through zonal statistics. Interpolation accuracy was assessed through leave-one-out cross-validation (LOOCV), in which each point was withheld in turn and re-estimated from the remaining 44 points; the resulting error statistics are reported in Section 3.3.

2.4. Classification of the MEQI

The hexagon-level MEQI score is classified into four bands using equal intervals across the 0–100 range (Table 2). An equal-interval scheme (intervals of 25 points) was adopted, as it does not require fitting thresholds to the observed data distribution, and the resulting four-category structure is consistent with the classification schemes reported for other composite mangrove indices (Faridah-Hanum et al., 2019; Mohamad Pazi et al., 2021; Rahmila et al., 2026).

Table 2
MEQI classification used in this study.

MEQI Score Range	Category (EN)	Interpretation
≤ 25	Poor	Badly degraded vegetation and/or water quality; a priority for rehabilitation.
25 < MEQI ≤ 50	Moderate	Partially degraded or disturbed; management intervention recommended.
50 < MEQI ≤ 75	Good	Reasonably developed structure and stable water quality; routine monitoring is enough.
> 75	Very Good	Close to reference condition; a candidate conservation or benchmark site.

2.5. Statistical Comparison of IWQ and ISV

To test whether the water-quality and vegetation-structure sub-indices diverged systematically across stations rather than incidentally, each of the 45 points was assigned to a functional (score > 50) or degraded (score ≤ 50) class for IWQ and ISV separately, following the classification boundary defined in Table 2. The two paired classifications were cross-tabulated into a 2 × 2 contingency table, and McNemar's test was used to evaluate whether the number of stations shifting from functional water quality to degraded vegetation structure differed from the reverse pattern. Because one of the two discordant cells was empty, McNemar's exact (binomial) test (McNemar, 1947) was used in place of the chi-square approximation. This test was implemented in R (R Core Team, 2024).

3. Results

3.1. PCA-Derived Weights

Applying principal component analysis separately to the two parameter sets yielded the indicator weights, which are presented alongside the minimum and maximum values used for standardization in Table 3. The first principal component, whose loadings were used to derive the reported weights, explained 41.41% of the total variance in the vegetation domain and 44.58% in the water-quality domain; together with the second component, cumulative variance explained reached 65.08% in the vegetation domain and 64.04% in the water-quality domain (Fig. 4). Sampling adequacy for PCA was confirmed by Bartlett's test of sphericity, which was significant for both domains (vegetation: $\chi^2 = 137.79$, df = 15, $p < 0.001$; water quality: $\chi^2 = 118.34$, df = 15, $p < 0.001$). The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was acceptable for the vegetation domain (KMO = 0.51) but below the conventional threshold of 0.5 for the water-quality domain (KMO = 0.36), indicating comparatively weaker intercorrelation among the six water-quality parameters. Within the water-quality domain, pH received the highest weight, followed by dissolved oxygen and salinity. Meanwhile, the three nutrient parameters received comparatively lower and more similar weights. On the other hand, the vegetation domain revealed that

carbon stock and biomass received the highest weights, canopy cover received an intermediate weight, and diameter, height, and stand density received comparatively lower, closely clustered weights. In both domains, the difference between the highest and lowest weight was modest (approximately 0.07), indicating that all six parameters within each domain contributed comparably to the index rather than any single variable dominating the result.

Table 3
PCA-derived weights and normalization bounds for the water-quality and vegetation structure parameters of 45 point stations across Segara Anakan lagoon, Central Java Province, Indonesia

Domain	Parameter	Direction	Min	Max	PCA Weight
Water Quality (IWQ)	pH	Positive (+)	6.55	8.06	0.2050
	Dissolved oxygen (mg L^{-1})	Positive (+)	4.00	9.10	0.1834
	Salinity (ppt)	Positive (+)	24.3	35.2	0.1726
	Nitrate (mg L^{-1})	Negative (–)	0.23	1.01	0.1531
	Ammonia (mg L^{-1})	Negative (–)	0.63	4.08	0.1470
	Phosphate (mg L^{-1})	Negative (–)	0.25	0.89	0.1389
Vegetation Structure (ISV)	Carbon stock (t C ha^{-1})	Positive (+)	0.040	5.997	0.2191
	Biomass (kg ha^{-1})	Positive (+)	5.17	1,846.33	0.2118
	Canopy cover (%)	Positive (+)	11.46	88.14	0.1588
	DBH (cm)	Positive (+)	1.31	9.07	0.1390
	Tree height (m)	Positive (+)	4.34	11.00	0.1383
	Stand density (ind. ha^{-1})	Positive (+)	64.99	22,877.94	0.1330

3.2. Index of Water Quality (IWQ), Vegetation Structure (ISV), and Mangrove Ecosystem Quality Index (MEQI)

IWQ ranged from 24.65 to 81.50, ISV spread wider from 11.43 to 81.01, and the composite MEQI ranged from 23.30 to 76.19 across the 45 points (Fig. 5). Classified according to the MEQI criteria, the composite scores comprised 2 stations rated as Very Good, 26 as Good, 15 as Moderate, and 2 as Poor. The difference between the two sub-indices is notable in itself. Water quality across Segara Anakan is, on average, in reasonably good condition (mean IWQ above 60), whereas vegetation structure is both lower on average and considerably more variable among stations. Moreover, McNemar's exact test

(Section 2.5) was conducted to evaluate whether this divergence between IWQ and ISV was systematic rather than incidental. Each station was assigned to a functional (Good to Very Good, score > 50) or degraded (Moderate to Poor, score ≤ 50) class for IWQ and ISV separately. Of the 45 stations, only 14 showed class synchronization, where both domains were either jointly functional (n = 6) or jointly degraded (n = 8). Crucially, across the remaining 31 stations, water quality remained functional while vegetation structure had deteriorated into the degraded class; conversely, no single station exhibited functional vegetation alongside degraded water quality. Because this 31-vs-0 split left one discordant cell empty, McNemar's exact (binomial) test was used, confirming the asymmetry was statistically significant ($p < 0.001$).

3.3. Spatial Distribution of the MEQI

Interpolating the 45 point values with IDW and summarizing them per hexagon produces a map that closely mirrors Fig. 5 (Fig. 6). The weaker, red-to-orange hexagons are concentrated along the eastern arm and central corridor of the lagoon, corresponding approximately to the M1- and M2-series stations, whereas the stronger, yellow-green to green hexagons cluster in the north-central and western sectors, around stations such as N-28, M1-9, TMB-20, and MT-6. Leave-one-out cross-validation of the IDW interpolation (inverse-distance power = 2) yielded a root-mean-square error of 10.53, a mean absolute error of 8.26, and an R^2 of 0.27 on the 0–100 MEQI scale, indicating moderate predictive accuracy consistent with the relatively sparse 45-point sampling network relative to the extent of the lagoon.

4. Discussion

4.1 The Spatial Health Index and Divergence Between Vegetation Structure and Water Quality

The application of the Mangrove Ecosystem Quality Index (MEQI) developed in this study provides a comprehensive quantitative overview of the spatial health status of the ecosystem at the time of data collection. Analysis across the 45 sampling stations generally reveals that 28 stations are classified as Good or higher, while 17 stations fall below this level. Spatially, the data collected during the peak of the dry season demonstrates that better environmental conditions are located in the western and northern regions of the lagoon, whereas degraded areas are concentrated in the east to the southeast, along with two specific spots in the south. These results exhibit an intriguing pattern, as they contrast with previous studies regarding the health and landscape structure of Segara Anakan. Vegetation conditions in the western sector were worse compared to the eastern sector, characterized by lower tree density due to high sedimentation from the Citanduy River and the spread of invasive species (*Derris trifoliata* and *Nypa fruticans*), presumably driven by increasing population density and proximity to settlements (Hilmi et al., 2021, 2022; Purwanto et al., 2025; Rahmila et al., 2026).

The divergence in the spatial health patterns of the mangrove ecosystem observed in this study stems from the difference in the measurement instruments utilized. Previous research generally relied on

vegetation parameters as the sole determinant of ecosystem health. Conversely, the present study employs a dual-index structure, comprising the ISV and IWQ, thereby directly incorporating the dynamic conditions of the aquatic environment at the time of observation. Vegetation structure is an accumulative reflection of environmental conditions over decades, whereas water quality is highly dynamic and strongly dependent on temporal variables, particularly the distinct wet and dry seasonal variations in tropical Indonesia. This is corroborated by the average ISV score (40.77), which is substantially lower than the average IWQ score (62.75). This disparity is further validated by McNemar's exact test, which confirmed a statistically significant class shift ($p < 0.001$). Across 31 observation stations, water quality was detected to be functional (score > 50), yet the underlying vegetation structure was already degraded (score ≤ 50).

The dominance of the water quality index over the vegetation structure index elucidates the higher MEQI scores observed in the western region. During the dry season when sampling was conducted, the input of pollutants and sediments from the Citanduy River into the western part of the lagoon decreased, coinciding with a lower volume of terrestrial water runoff. Simultaneously, the eastern side of the lagoon continues to receive a relatively constant load of land-derived substances from the industrial and household activities of Cilacap City. This anthropogenic impact is also detected in the two "Poor" categorized zones located in the south, which coincide with local residential areas. This hydrological pattern aligns with findings from similar seasonal timeframes by Dsikowitzky et al. (2011), Jennerjahn & Yuwono (2009), Kusumaningtyas et al. (2019), and Prayoga et al. (2021), who also recorded higher contaminant loads in the eastern waters compared to the west during the dry season. Consequently, combining ISV and IWQ into the MEQI successfully captures the comprehensive actual state of the ecosystem. However, it concurrently issues a critical caveat: temporally improved water quality can create a masking effect, obscuring the reality that the mangrove vegetation structure in the western part of Segara Anakan remains historically degraded.

4.2 PCA Empirical Weighting and MEQI's Position Compared to Other Indices

The empirical weighting derived from the principal component analysis (PCA) provides ecological insights into the variables driving ecosystem conditions within the Segara Anakan lagoon. Within the vegetation structure parameters, aboveground carbon stock and biomass received the highest weights. This corresponds to their function as cumulative indicators of stand development, effectively differentiating young, low-density stands from dense, mature forests (Panda et al., 2025; Ratul et al., 2024). Meanwhile, within the water quality parameters, pH and DO received weights exceeding those of nutrient variables. This aligns with the predefined weights established by the National Sanitation Foundation Water Quality Index, which similarly assigns higher weights to DO and pH (0.17 and 0.11, respectively) compared to the nitrate variable (0.1) representing nutrients (Vasistha & Ganguly, 2020). DO and pH exhibit broader variance fluctuations in distinguishing inter-station quality, unlike nutrient loads which tend to be concentrated at specific runoff points and are generally high in tropical waters like those in Indonesia.

Nevertheless, the modest variance in weights generated by the PCA (approximately 0.07 between the highest and lowest) indicates that all variables contribute proportionally and meaningfully, preventing any single variable from disproportionately dominating the index. Other studies, such as the five-index framework applied to the Hung Yen Mangrove in Vietnam and trophic index monitoring in southern Brazil, have adopted a congruent approach, utilizing PCA-based mangrove water quality assessments (Nguyen et al., 2026; Rodrigues et al., 2026). This PCA-based weighting approach is conceptually related to the AHP weighting employed by Wang et al. (2026), but with a crucial modification: the resulting weights are not predefined by specific expert judgments, which can be subjective, but are instead objectively derived from the data distribution of the variables present at the observation sites.

The integration of both vegetation and water components serves as the primary value-added feature of the MEQI. If monitoring relies solely on a vegetation structure-based index (such as ISV), the results will only depict generalized and historical spatial patterns. Meanwhile, in coastal environments characterized by dynamic aquatic components, the structural and water quality recovery of mangrove ecosystems do not necessarily proceed on the same timeline (Lonergan et al., 2026; Pradit et al., 2026). In contrast, the MEQI, through its incorporation of the IWQ, is capable of directly capturing temporal dynamics linked to actual environmental conditions. Without the separation and subsequent integration of these two sub-indices, utilizing a composite score alone risks classifying sites as uniformly moderate when they might be structurally intact but functionally impaired in terms of water quality (as observed in the eastern sector of the Segara Anakan lagoon), or vice versa, thereby masking the specific dimension that requires restorative intervention.

MEQI exhibits distinct characteristics by consolidating two major parameters (ISV and IWQ), when compared to several existing mangrove aquatic environmental quality indices. In terms of scope, the MEQI is narrower than the Mangrove Quality Index proposed by Faridah-Hanum et al. (2019), which necessitates additional socio-economic and marine variables. Conversely, the MEQI's scope is broader than that of the Mangrove Sediment Quality Index developed by Mohamad Pazi et al. (2021), which specifically targets heavy metal contamination. Methodologically, the MEQI serves as a complement to the mangrove health index we previously developed, namely the Mangrove Ecosystem Health Index (MEHI). The MEHI, also developed for the same lagoon, is based on satellite imagery, hexagonal-grid landscape metrics, and distance-to-disturbance layers without requiring field sampling, making it highly suitable for areas with restricted access (Rahmila et al., 2026). Meanwhile, the MEQI is an instrument that can be readily deployed in locations with ground access, as it solely requires basic forestry tools and a portable water-quality meter, thereby eliminating the need for remote-sensing workflows or expensive socio-economic and laboratory surveys.

4.3 Limitations, Future Directions, and Implications for Management

Several limitations warrant acknowledgment. The minimum and maximum values used for standardization and the PCA-derived weights are both specific to this 45-point survey. Applying the same

standardization values and PCA weights to a different lagoon without recalibration might not be appropriate and whether a repeat survey across different seasons at Segara Anakan itself would yield similar weights remains to be tested. The Kaiser-Meyer-Olkin measure for the water-quality parameter set (KMO = 0.36) fell below the conventional threshold of 0.5, indicating that these six parameters are less strongly intercorrelated than the vegetation parameters (KMO = 0.51); the water-quality weights should therefore be interpreted with some caution, and future studies should consider refining the parameter set to improve intercorrelation for PCA. A sample of 45 points is also relatively sparse for IDW interpolation across a lagoon of this extent, and denser sampling around the two Poor-classified stations in particular would improve the spatial resolution of the resulting map. This sparsity is reflected in the leave-one-out cross-validation accuracy of the interpolated surface (R^2 = 0.27; Section 3.3), which, while adequate for identifying broad spatial patterns, indicates that point-level predictions away from sampled stations carry non-trivial uncertainty. Finally, the index as constructed considers only physicochemical water-quality and structural vegetation parameters; incorporating sediment biogeochemical indicators or biological water-quality indicators, such as benthic macroinvertebrate metrics, represents a reasonable direction for future refinement, and would bring the MEQI closer in scope to more comprehensive tools such as the MQI while retaining its field-based, low-infrastructure design.

The implications of these research findings for mangrove conservation management underscore that the mangrove ecosystem functions as a highly dynamic coastal environment. Point-in-time assessments relying exclusively on vegetation structure obscure the temporal fluctuations of aquatic conditions, which can vary significantly with the seasons. Consequently, periodic monitoring that integrates these dynamic parameters is imperative for achieving a more holistic understanding of the environmental state. Furthermore, the concurrent application of the MEHI and MEQI offers two complementary approaches for the environmental management of mangrove conservation. While landscape-scale mapping via the MEHI yields an overview analogous to the ISV, portraying mangrove structural health as the spatio-temporal accumulation of environmental conditions, the MEQI serves as an essential monitoring complement designed to periodically capture the actual temporal dynamics of the aquatic environment.

5. Conclusion

This study successfully developed and applied the field-deployable Mangrove Ecosystem Quality Index (MEQI) across 45 points in the Segara Anakan lagoon, fulfilling the critical need to integrate vegetation structure (ISV) and water quality (IWQ) into a single assessment. By employing PCA-derived empirical weights, the index objectively captured the ecosystem's condition, yielding a lagoon-wide average MEQI of 51.76. Spatial mapping via a hexagonal grid successfully identified the eastern and central corridors as primary rehabilitation priorities, while the western and north-central sectors maintained healthier baseline conditions. Crucially, examining the sub-indices independently revealed that vegetation structure (average ISV 40.77) currently constrains the lagoon's recovery significantly more than water quality (average IWQ 62.75). This divergence demonstrates that utilizing a composite score alone risks a critical masking effect, wherein temporally functional water quality conceals historically degraded

vegetation. The MEQI proves to be a highly practical, low-infrastructure complement to remote-sensing tools like the MEHI. Moving forward, incorporating the MEQI into regular conservation monitoring will allow environmental managers to accurately decipher the distinct temporal and spatial dynamics of mangrove ecosystems, ensuring that targeted restoration interventions address both structural and aquatic impairments concurrently.

Declarations

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Author contributions

Yulizar Ihrami Rahmila: conceptualization, methodology, field data collection, formal analysis, writing – original draft, project administration.

Izhamil Hidayah: field data collection, vegetation data curation.

Suyadi Suyadi: methodology, vegetation data collection, spatial analysis.

Dafit Ariyanto: field data collection, data curation.

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Varenna Faubiany: data curation, visualization.

Rinny Rahmania: field data collection, data curation.

Marwan Setiawan: field data collection, resources.

Ani Haryati: laboratory analysis, data curation, review and editing.

Novalia Rachmawati: methodology, statistical analysis, review and editing.

Hedi Indra Januar: methodology, water quality data analysis, writing - review and editing, supervision, funding acquisition.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Consent

This study did not involve human participants, interviews, or community engagement; no consent procedures were required.

Ethical approval

This study involved only field ecological and water-quality measurements, with no human or animal subjects; formal ethical approval was therefore not required, and all fieldwork followed standard ethical research conduct.

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Data Availability Statement

The field dataset analyzed in this study (raw measurements, normalized values, and station-level IWQ, ISV, and MEQI scores for all 45 sampling points) is available from the corresponding author upon reasonable request.

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Figures



Figure 1

Study area, showing mangrove cover (green) and the 45 sampling points (red dots) across Segara Anakan, Cilacap Regency, Central Java.

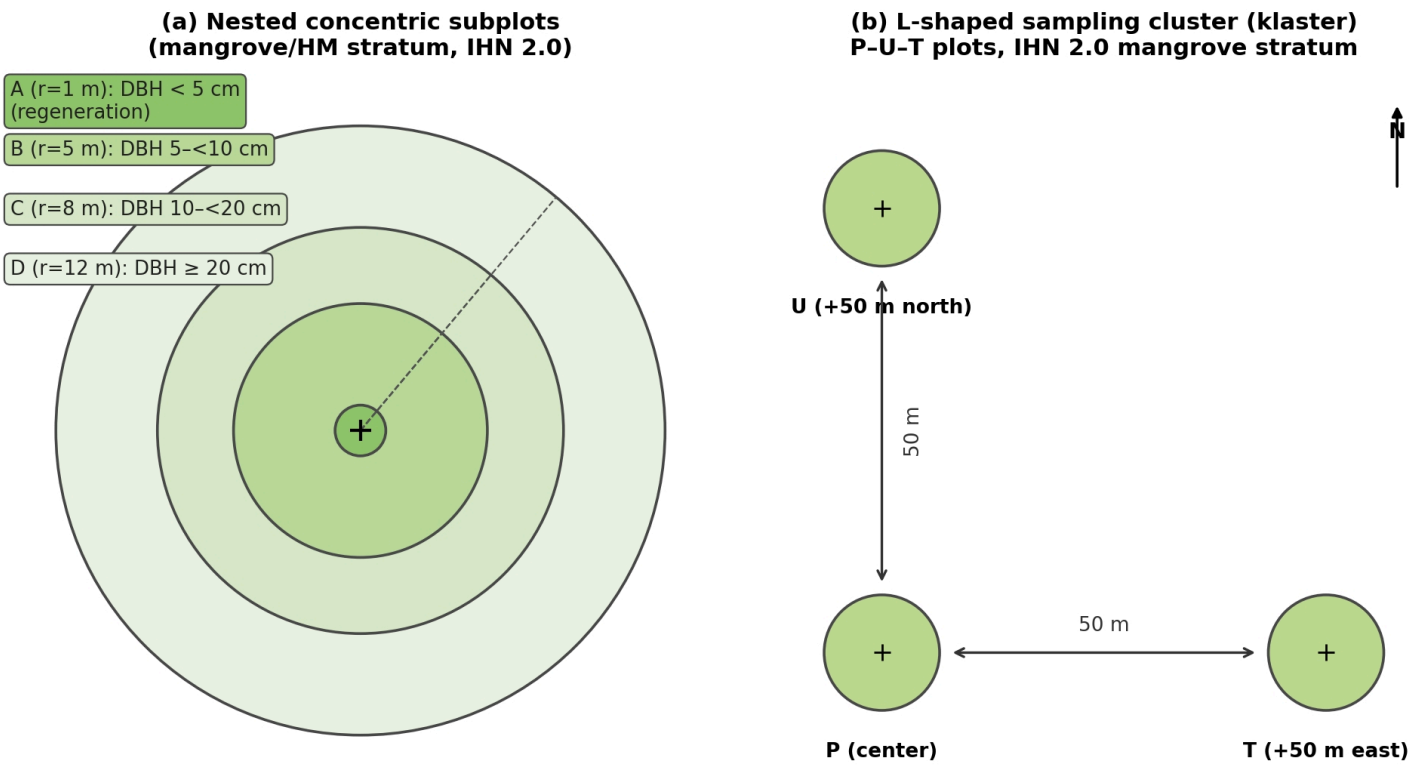


Figure 2

Mangrove-stratum plot design under IHN 2.0. (a) The four nested subplots (A–D), each tied to a diameter class, with a stem counted only once in whichever subplot matches its size. (b) The national three-plot cluster (P–U–T); this study used only the single-plot geometry in (a) at each of the 45 points.

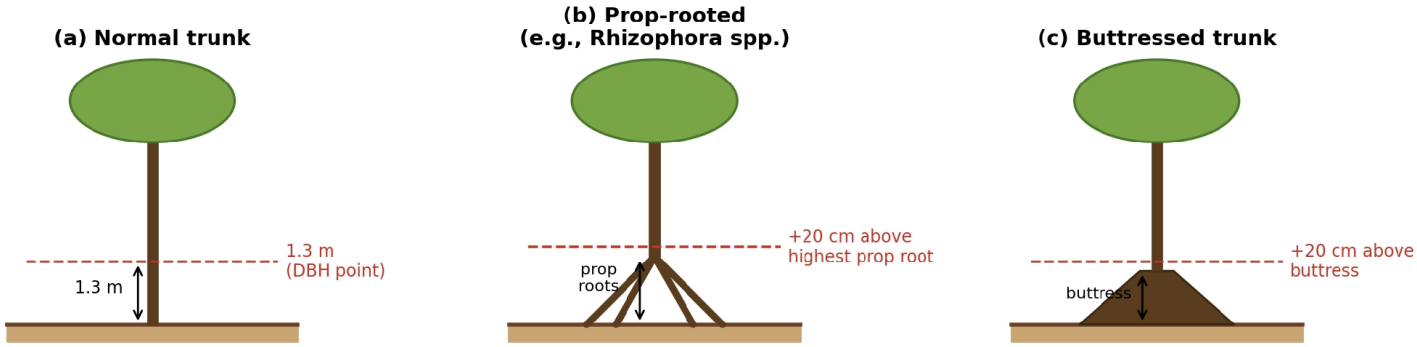


Figure 3

Where diameter was measured on each mangrove growth form: (a) a normal trunk, at 1.3 m; (b) a prop-rooted tree such as Rhizophora, 20 cm above the highest prop root; (c) a buttressed trunk, 20 cm above the buttress.

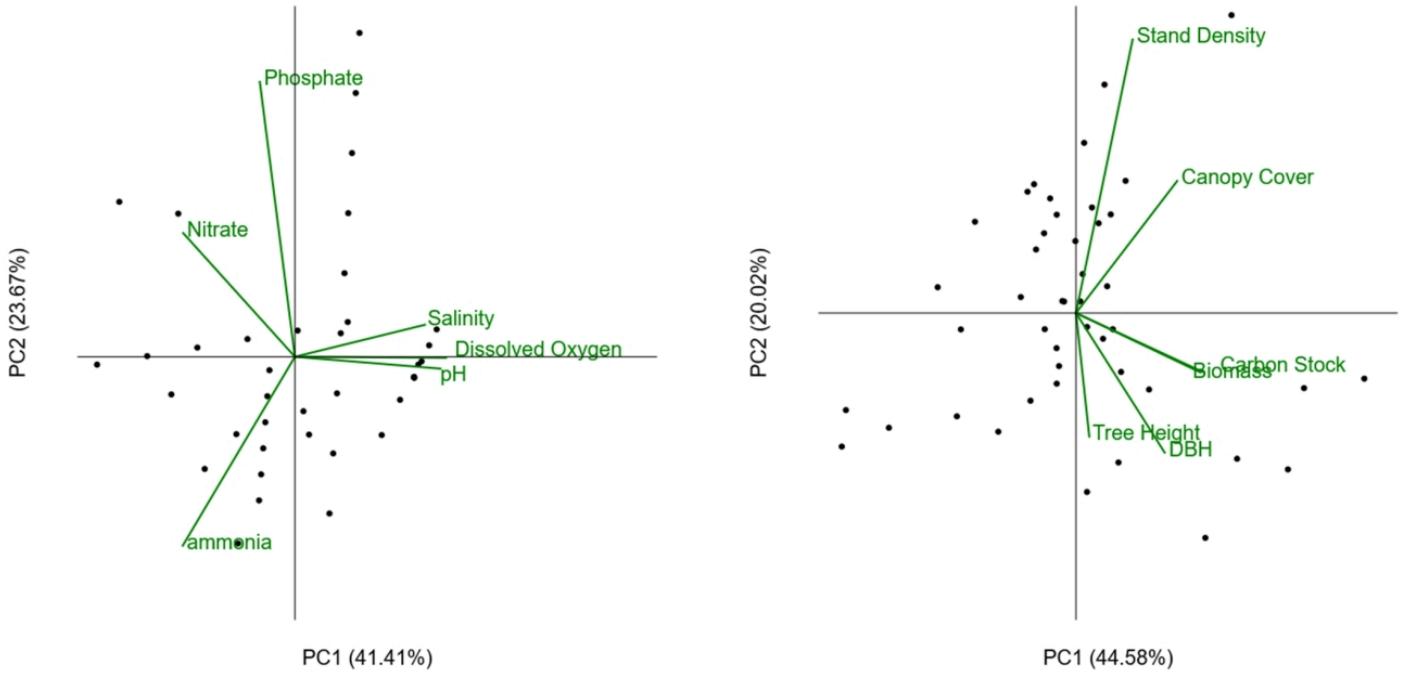


Figure 4

Principal component analysis of vegetation structure (a) and water quality (b) of 45 point stations across Segara Anakan lagoon, Central Java Province, Indonesia

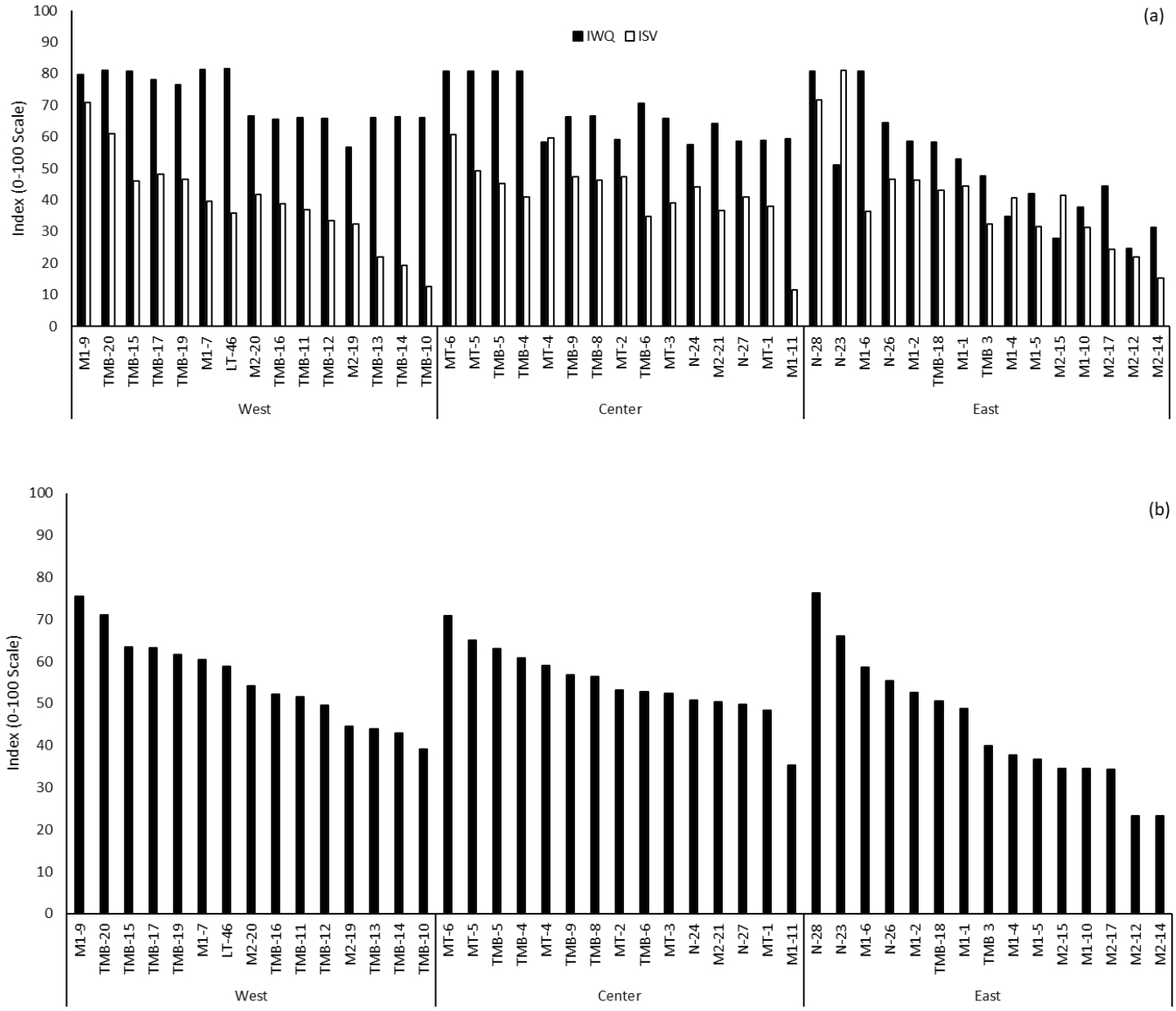


Figure 5

IWQ, ISV, composite MEQI, and condition category across the 45 sampling stations in Segara Anakan lagoon, Central Java Province, Indonesia, ranked from highest to lowest MEQI

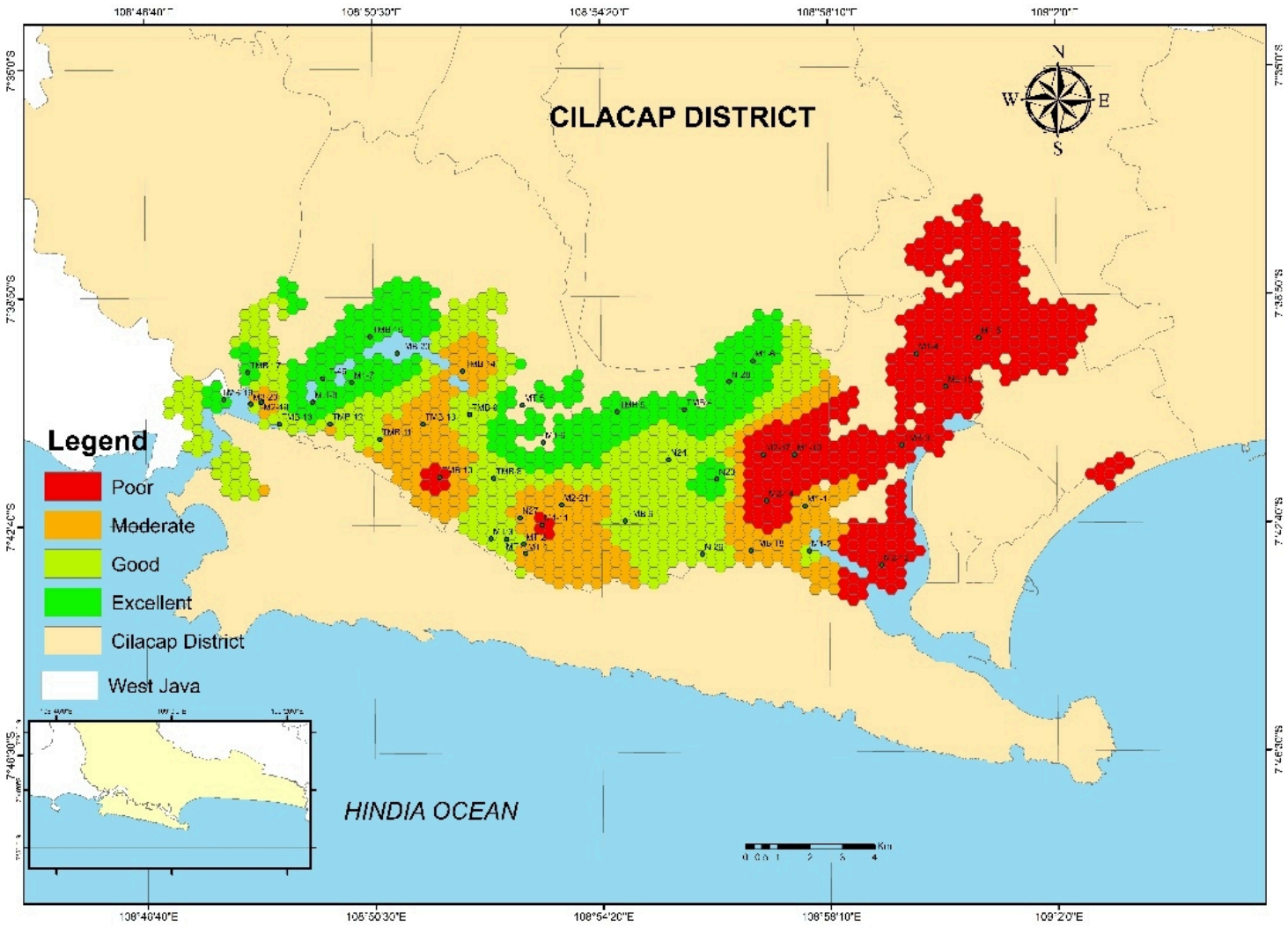


Figure 6

MEQI across Segara Anakan, from IDW interpolation of the 45 point values followed by zonal statistics per hexagon