Journal of Health and Nutrition Research
Vol. 4, No. 1, 2025, pp. 287-300, https://doi.org/10.56303/jhnresearch.v4i1.380
Journal homepage: https://journalmpci.com/index.php/jhnr/index

e-ISSN: **2829-9760**

Coastal Water Quality Index (CWQI) Assessment of Youtefa Bay, Jayapura: Status and Management Implications

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ORIGINAL ARTICLES

Submitted: 20 March 2025

Accepted: 25 April 2025

Keywords:
Anthropogenic Activities, Coastal Management, Eutrophication, Mangrove Ecosystem, Water Quality Index

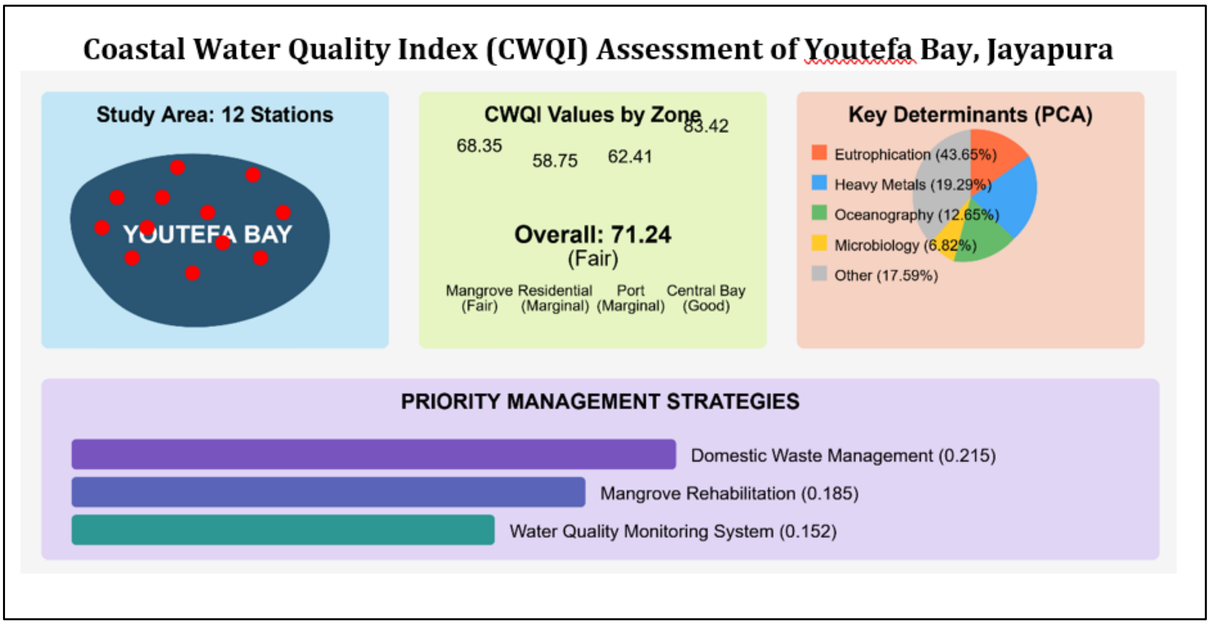
ABSTRACT

This research aims to assess the water quality status of Youtefa Bay in Jayapura City using the Coastal Water Quality Index (CWQI) method. Youtefa Bay is an important ecological area with mangrove, seagrass, and coral reef ecosystems that currently face anthropogenic pressures. A quantitative approach with descriptive analytical design was conducted through sampling at 12 stations during the dry season (June) and rainy season (November) 2024. Parameters measured included physical aspects (temperature, transparency, turbidity, TSS, salinity), chemical aspects (pH, DO, BOD, COD, nitrate, phosphate, ammonia, heavy metals), and biological aspects (chlorophyll-a, coliform, E. coli, phytoplankton). Results showed that the overall CWQI value for Youtefa Bay was 71.24 (classified as "Fair"). Significant spatial variation was observed with residential zones having the lowest CWQI (58.75, "Marginal"), port zones (62.41, "Marginal"), mangrove zones (68.35, "Fair"), and the central bay area having the highest value (83.42, "Good"). Principal Component Analysis identified eutrophication-related parameters (turbidity, TSS, BOD, nitrate, phosphate) as the main determinants of water quality, contributing 43.65% of the total variance. Temporal analysis showed lower water quality during the rainy season (CWQI=62.8) compared to the dry season (CWQI=74.5). Strong correlations were found between anthropogenic activities and water quality, with population density negatively correlated (r=-0.854) and mangrove cover positively correlated (r=0.765). Sustainable management strategies were formulated, prioritizing domestic waste management, mangrove rehabilitation, development of integrated monitoring systems, community empowerment, and strengthening stakeholder coordination. This research provides a scientific basis for effective bay management.

Key Messages:

- Youtefa Bay's overall water quality is classified as "Fair" according to the Coastal Water Quality Index, with significant spatial degradation observed in anthropogenic-influenced zones, particularly residential and port areas, highlighting the impact of localized human activities.

GRAPHICAL ABSTRACT



INTRODUCTION

Youtefa Bay is a small bay of about 1,675 hectares located in the southern part of Jayapura city, Papua, Indonesia (1–3). This area has a diverse ecosystem including mangrove forests, seagrass beds, and coral reefs that are habitats for various marine biota (4,5). Although it has been designated as a Nature Tourism Park since 1996, Youtefa Bay is currently facing significant environmental pressures due to rapid development and population growth in Jayapura City. Various anthropogenic activities such as domestic waste disposal, garbage, sedimentation, and port activities have negatively impacted the quality of the Gulf waters, characterized by increased turbidity, decreased dissolved oxygen levels, and the discovery of contaminants in the form of heavy metals and coliform bacteria at several points in the Gulf waters (6). This condition is further exacerbated by the lack of effective management implementation, despite its conservation area status (7).

The elevated turbidity levels in Youtefa Bay pose significant threats to the marine environment and tourism potential of the area. High turbidity reduces light penetration in water, impacting photosynthesis and the overall health of aquatic ecosystems. This can lead to decreased oxygen levels, altered food chains, and potential loss of biodiversity (8). The excessive turbidity also diminishes the aesthetic value of the Bay, potentially deterring tourists and affecting the local economy that relies on marine-based activities. Moreover, the presence of heavy metals like lead (Pb) and cadmium (Cd) in concentrations exceeding regulatory limits further compounds the environmental challenges in Youtefa Bay. These toxic elements can bioaccumulate in marine organisms, leading to long-term ecological damage and posing health risks to humans consuming contaminated seafood (9). Addressing these issues is crucial for preserving the Bay's ecosystem services, protecting public health, and ensuring the sustainable use of marine resources in the region.

The decline in marine biodiversity has profound implications for both ecosystems and local communities. A reduction in coral cover, primarily due to sedimentation and eutrophication, not only damages reef structures but also hinders their natural recovery (10,11). Similarly, the degradation of seagrass beds disrupts critical nursery habitats for marine species and compromises water quality (12). The disappearance of mollusks and crustaceans from traditional fishing areas further signals ecosystem instability. These environmental changes significantly affect Indigenous communities that rely heavily on the Bay’s natural resources. As key species become scarce, food security and economic resilience are

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threatened, while the loss of biodiversity simultaneously undermines cultural heritage closely tied to the marine environment.

The ecosystem of Youtefa Bay has important values, both ecologically and socio-culturally. Ecologically, this Bay plays a role in maintaining the balance of the coastal environment, while socio-culturally, this Bay has a deep cultural value for Indigenous Papuans, especially the Enggros and Tobati tribes who have lived side by side with the Bay ecosystem for centuries (13). The ecological conditions of Youtefa Bay directly impact the food security and economy of coastal communities who depend on the Bay's fishery resources for their livelihoods (14) (15). According to Zhou W et al (2024) (16) revealed that the degradation of water quality not only threatens biodiversity, but also has the potential to cause social conflicts related to the use of increasingly limited resources.

Previous studies on Youtefa Bay have generally been partial and fragmented, focusing on certain aspects without providing a comprehensive picture of the overall health status of the Bay's waters (17,18) Most studies only measure basic physicochemical parameters without integrating them into an easily interpretable index (19). Significant gaps are also seen in the lack of temporal studies, so that the dynamics of changes in the quality of the Bay's waters over time have not been properly mapped (20). Furthermore, no study has specifically applied the Coastal Water Quality Index (CWQI) method in Youtefa Bay with its unique tropical water characteristics, even though this method has been proven effective in evaluating the quality status of coastal waters in various parts of the world (15,21).

Applying the CWQI method to assess the quality status of the waters of Youtefa Bay is an important breakthrough bridging this knowledge gap. Supardiono S et al (2024) (22) and Chemeri L et al (2023) (23) argue that this method offers an integrative approach by considering various physical, chemical, and biological parameters simultaneously, to provide a more complete picture of the condition of the bay waters. The results of the application of CWQI will be a strong scientific basis for decision-making and the formulation of more effective and data-based bay management policies (24). Moreover, this research comes amidst the urgency to save the increasingly stressed Youtefa Bay ecosystem, hoping to create synergy between the traditional knowledge of indigenous peoples and modern scientific approaches in efforts to conserve and sustainably manage this Bay.

METHODS

This study used a quantitative approach and analytical descriptive design to assess the quality of the waters of Youtefa Bay. Sampling was conducted at 12 stations in June 2024 (representing the dry season) and November 2024 (representing the rainy season), covering mangrove zones, settlements, docks, and the middle of the Bay. The 12 research stations can be seen in Figure 1.

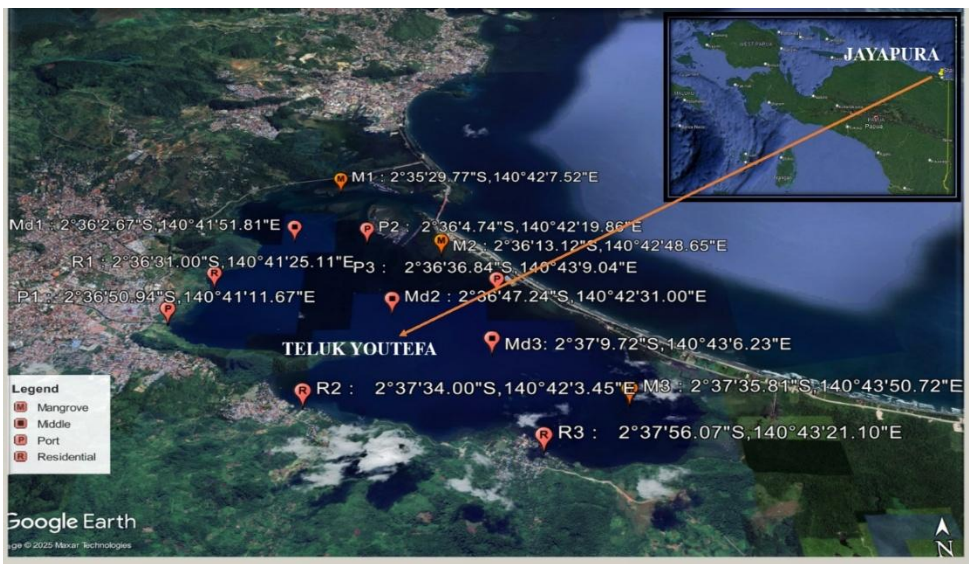

Figure 1. Research stations

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Researchers used various equipment such as GPS, water quality checker, and plankton net. Parameters measured include aspects of physics: temperature, brightness, turbidity, TSS (Total Suspended Solids), and salinity, parameters chemistry: pH (Potential of Hydrogen), DO (Dissolved Oxygen), BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), nitrate, phosphate, ammonia, heavy metals), and biology (chlorophyll-a, coliform bacteria, *E. coli*, phytoplankton).

Primary data collection was carried out through direct measurements in the field and laboratory analysis, with samples taken at a depth of 0.5 meters and stored at a temperature of 4 °C. Secondary Data included meteorological data, land use, demographics, and past research. Water quality status was analyzed using the Coastal Water Quality Index (CWQI) method*, which was* developed by CCME and modified for coastal waters.

1. Evaluation of Water Quality Status using CWQI

To evaluate water quality status, the CWQI method was adapted from the Canadian Water Quality Index with modification for the waters coast by Sari A et al. [16].CWQI was employed. It was calculated with formula:

$$CWQI = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732}\right)$$ ………………………………………….. ….(1)

Note:

- F_1 F1 $= \frac{\text{number of parameters that do not meet the quality standard}}{\text{total number of parameters measured}}$) x 100%
- $F2_2 = \frac{\text{number of test results that do not meet quality standards}}{\text{total number of tests}}$) x 100%
- F_3 F3 $= \frac{nse}{\text{total number of tests}}$) x 100%
- $nse = \frac{\sum_{i=1}^{n} excursion}{the\ total\ number\ of\ tests}$, and *excursion* is calculated as the deviation of the value of the test results against the quality standard.

The CWQI results were interpreted in categories: excellent (95-100), good (80-94), fair (65-79), marginal (45-64), and poor (0-44) (25,26). Determination of the quality of each water quality parameter used Government Regulation No. 22 of 2021) (27), attachment viii concerning Sea Water Quality Standards.

2. Identification of the main determinants of water quality

To identify the water quality parameters that became the main determining factor, the Principal Component Analysis (PCA) method proposed by (28) with the model:

$$Z = a_1F_1 + a_2F_2 + ... + a_mF_m + e$$ ………………………………….. ….(2)

Note: Z iss the standardized water quality parameter, F $_{FJ}$ is the main component, a $_{AJ}$ is the loading factor, and *e* is the error. Component extraction using eigenvalue>1 criterion and varimax rotation to clarify the interpretation. Parameters with factor loading>0.7 were set as main quality waters' determinants (29).

3. Analysis of spatial and Temporal variations of Water Quality

Spatial variation was analyzed using the ordinary kriging method with a semivariogram model:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$ …………………………… …(3)

Note: γ(h) iss a semivariogram, Z(x_i) is the value of the parameter at location xi xi , and N (h) is the number of pairs of points with distance h. Hierarchical Alister Analysis (HCA) with Ward's method and Euclidean distance was used to Group stations based on the similarity of water quality characteristics:

$$d(x, y) = \sqrt{\sum_{i=1}^{n} (x_i - y_i)^2}$$ ………………………………………… …(4)

For temporal variation, a one-way ANOVA (Analysis of Variance) test with a model was used:

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$$Y_{ij} = \mu + \tau_i + \varepsilon_{ij}$$ ………………………………………….. ….. (5)

Note: Y_{ij} is observation to -j of season i-th, μ is the general average, τ_i is effect season, and ε_{ij} is error (30).

4. Relationship of anthropogenic activity to water quality

The relationship between anthropogenic activity and water quality was analyzed using the Spearman correlation:

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)}$$ ………………………………………….. …(6)

Note: d_i is the difference in rank and n is the amount of data. Next, multiple regression with stepwise method was used:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \varepsilon$$ …………………………… …(7)

Note: Y is the CWQI, X_i is the environmental parameter (population density, distance from polluting sources, percentage of land cover), ε_i is the regression coefficient, and ε is the error (31).

5. Formulation of Sustainable Management Strategies

Management strategy formulated based on SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis that identified the Strengths, Weaknesses, Opportunities, and Threats of condition Bay Youtefa. The resulting alternative strategy evaluated using the Analytical Hierarchy Process (AHP) with calculation weight priority (32–34):

$$w_i = \frac{\sqrt[n]{\prod_{j=1}^{n} a_{ij}}}{\sum_{k=1}^{n} \sqrt[n]{\prod_{j=1}^{n} a_{kj}}}$$ ………………………………….. ….. (8)

Note: w_i is the priority weight of alternative I, a_{ij} is the pairwise comparison value between alternatives I and j, and n is the number of alternatives. Consistency evaluation tested used *Consistency Ratio* (35):

$$CR = \frac{CI}{RI} = \frac{\lambda_{max} - n}{(n-1)\times RI}$$ ………………………………….. …(9)

Note: CR<0.1 is considered consistent (36).

Data Analysis

Statistical analysis was conducted using appropriate software tools. The CWQI, adapted from the Canadian Water Quality Index for coastal waters, was calculated using Excel and R for their formula and dataset flexibility. PCA to identify key water quality determinants used SPSS for factor extraction and interpretation. Spatial analysis and kriging interpolation were conducted using ArcGIS and QGIS for geostatistical mapping. Temporal variations were analyzed using one-way ANOVA, while station clustering used HCA with Ward's method in SPSS. The relationship between anthropogenic activities and water quality was examined through Spearman correlation and stepwise multiple regression in SPSS. SWOT analysis was conducted with Excel, while AHP including pairwise comparisons was performed using Super Decisions software.

RESULTS

The results of the application of methods to achieve the objectives of the study are in the form of research results and discussions that will be described as follows.

Youtefa Bay Water Quality Status based on CWQI

The quality status of Youtefa Bay waters was evaluated using the CWQI method by comparing 17 water quality parameters measured at 12 research stations to the quality standards set out in Government Regulation No. 22 of 2021 (27). Figure 2 shows the CWQI scores across different zones of Youtefa Bay. The Central Bay shows the highest water quality with a CWQI of 83.42, categorized as *Good*. In contrast, the Residential and Port zones fall into the *Marginal* category with scores of 58.75 and 62.41, respectively,

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indicating significant pollution pressure. The Mangrove zone scores 68.35, which is classified as *Fair*, while the overall water quality of the bay is also rated *Fair*, with a CWQI of 71.24. These variations highlight the need for focused management efforts, especially in more degraded areas.

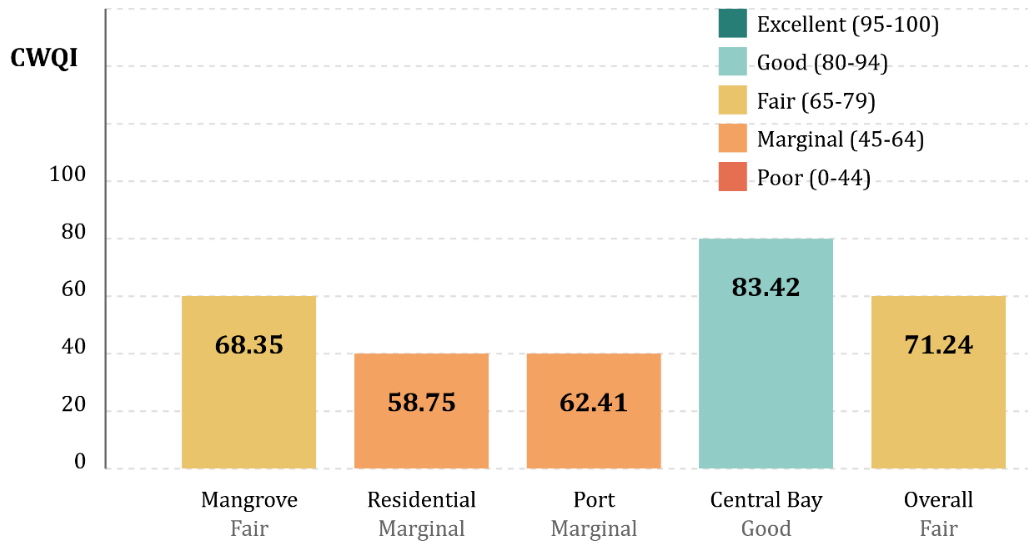

Figure 2. The CWQI Value by Zone

Temporal variation was also observed during the study period (Table 1), where the CWQI value in the rainy season (October-March) was significantly lower (62.8) than that in the dry season (April-September), with a CWQI value of 74.5 ($p<0.001$). The decline in water quality during the rainy season is mainly due to increased runoff from land that carries sediment and nutrients to the Gulf waters.

Table 1. Seasonal Variation in Coastal Water Quality Index (CWQI) in Yotefa Bay

Season	CWQI Value (Mean)	Description	p-value
Rainy Season	62.8	Lower water quality due to increased runoff carrying sediment and nutrients	<0.001
Dry Season	74.5	Higher water quality, less runoff impact	

Note: Significant difference at α = 0.05 according to T-test analysis

The Main Determining Factors For The Quality Of The Waters Of Youtefa Bay

As seen in Figure 3, Principal Component Analysis (PCA) revealed that eutrophication is the dominant factor influencing water quality in Youtefa Bay, accounting for 43.65% of the total variance. This component is characterized by high loadings of turbidity (0.842), total suspended solids (TSS) (0.796), biochemical oxygen demand (BOD_5) (0.715), nitrate (0.824), and phosphate (0.815), indicating significant nutrient enrichment and organic pollution. The second major component, representing heavy metal contamination, contributes 19.29% to the variance and includes lead (Pb) (0.795), cadmium (Cd) (0.848), and mercury (Hg) (0.831), reflecting potential inputs from industrial or anthropogenic sources. Oceanographic parameters, primarily salinity (-0.854), form the third component and explain 12.65% of the variation, suggesting hydrological influences on water quality. The fourth component, microbiological contamination, explains 6.82% and is represented by total coliform (0.824) and Escherichia coli (0.815), highlighting the impact of domestic waste. The remaining 17.59% of variation is attributed to other less significant components. These findings underscore the need for integrated water quality management addressing eutrophication, toxic pollutants, and microbial risks.

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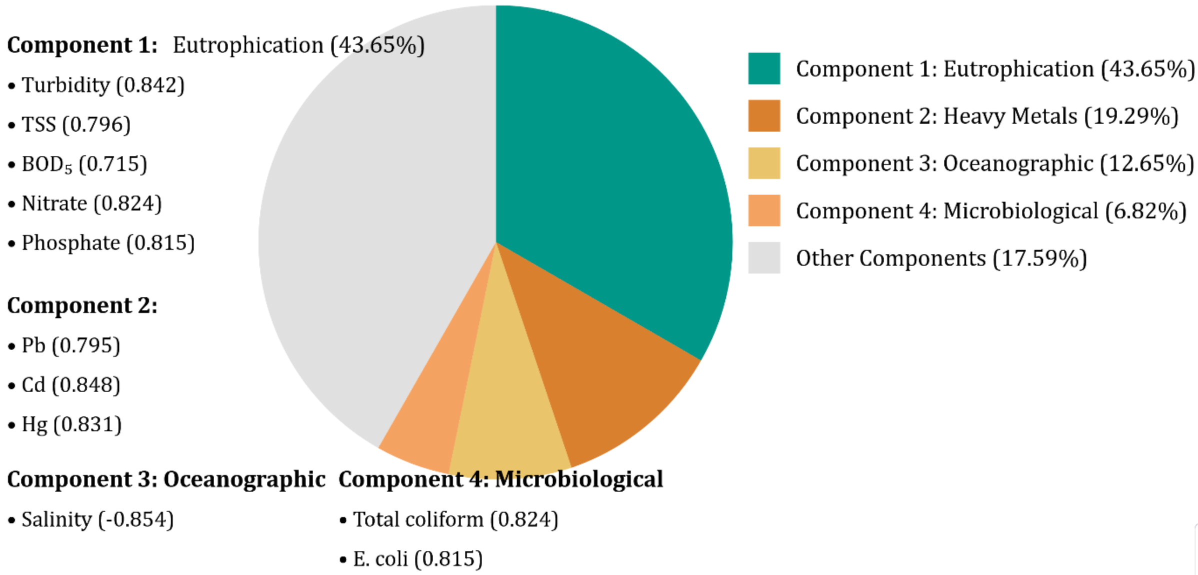

Figure 3. Contribution of the main components in the variation of water quality

Spatial and Temporal variations of Water Quality

Spatial Variation

The spatial distribution of water quality in Youtefa Bay reveals a clear gradient influenced by anthropogenic activities and proximity to settlement areas (Table 2). Hierarchical cluster analysis categorized the 12 observation stations into three distinct clusters, each representing a different level of water quality. Cluster 1, comprising stations 4, 5, and 6, is characterized by the lowest CWQI values and represents the residential zone, which is heavily influenced by runoff and domestic waste from nearby settlements. Cluster 2 includes stations 7, 8, 9, and 3, and exhibits moderate water quality. These stations are located in port areas and mangrove zones situated near human habitation, reflecting a mixture of natural filtration and localized pollution pressures. In contrast, Cluster 3, encompassing stations 1, 2, 10, 11, and 12, corresponds to areas with the highest CWQI values, indicating better water quality. These stations are located in relatively undisturbed mangrove areas and the central parts of the bay, away from direct anthropogenic impacts, highlighting the importance of spatial context in influencing water quality dynamics.

Table 2. Cluster-Based Spatial Distribution of Water Quality in Youtefa Bay

Cluster	Stations	Water Quality	Zone Description
Cluster 1	4, 5, 6	Worst (Low CWQI)	Residential zone (close to settlements)
Cluster 2	7, 8, 9, 3	Medium (Moderate CWQI)	Port zones and mangrove areas near settlements
Cluster 3	1, 2, 10, 11, 12	Best (High CWQI)	Mangrove zone away from settlements and middle of the Bay

Temporal Variations

The comparative analysis of water quality parameters between the dry and rainy seasons in Youtefa Bay reveals significant seasonal variations (Figure 4), particularly in indicators related to eutrophication. During the rainy season, turbidity (13.8 NTU) and total suspended solids (TSS) (48.6 mg/L) were markedly higher than in the dry season (7.9 NTU and 32.4 mg/L, respectively), likely due to increased surface runoff carrying sediments and pollutants into the bay. Dissolved oxygen (DO) levels also increased slightly in the rainy season (5.8 mg/L) compared to the dry season (4.8 mg/L), possibly due to enhanced water mixing and aeration. Nutrient concentrations, including nitrate and phosphate, were elevated in the rainy season (0.32 mg/L and 0.14 mg/L, respectively) relative to the dry season (0.18 mg/L and 0.07 mg/L), indicating a higher potential for eutrophication. Interestingly, despite the increased pollutant loads

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during the rainy season, the Coastal Water Quality Index (CWQI) was higher at 74.5, compared to 62.8 in the dry season, suggesting that certain parameters, such as improved oxygenation, may have partially offset the negative impacts, resulting in an overall "*fair*" classification. These findings highlight the importance of seasonal dynamics in coastal water quality assessment and underscore the need for adaptive management strategies.

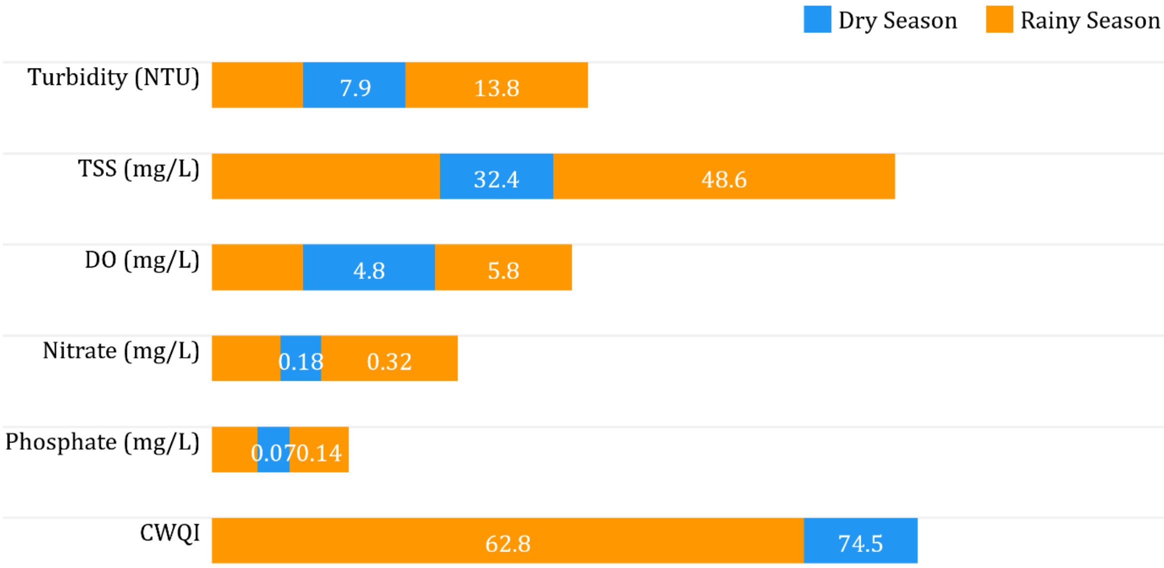

Figure 4. Comparison of water quality parameters by season

Relationship of anthropogenic activity to water quality

The relationship between anthropogenic activities and water quality in Youtefa Bay shows a clear pattern based on Spearman correlation and multiple regression analyses, displayed in Table 3. Population density exhibited a strong negative correlation with CWQI values (r = -0.854), indicating that higher human concentration tends to degrade water quality. Conversely, greater distances from settlements (r = 0.872) and ports (r = 0.728), along with a higher percentage of mangrove cover (r = 0.765), were positively associated with improved water quality. In contrast, increased coverage of settlements and open land showed significant negative correlations (r = -0.823 and r = -0.675, respectively). The regression model further supports these findings, demonstrating that 84.2% of the variation in CWQI can be explained by population density, settlement distance, and mangrove coverage, underscoring the substantial influence of land use and human proximity on coastal water conditions.

Table 3. Relationship between anthropogenic activity and water quality in Youtefa Bay based on Spearman correlation and multiple regression analysis

Anthropogenic Variable	Correlation with CWQI	Correlation Coefficient (r)	Effect Direction
Population Density	Negative	-0.854	Decreases CWQI
Distance from Settlements	Positive	0.872	Increases CWQI
Distance from Ports	Positive	0.728	Increases CWQI
% Mangrove Cover	Positive	0.765	Increases CWQI
% Settlement Cover	Negative	-0.823	Decreases CWQI
% Open Land Cover	Negative	-0.675	Decreases CWQI

Youtefa Bay Sustainable Management Strategy

Based on the SWOT analysis and its subsequent evaluation using the Analytical Hierarchy Process (AHP), seven priority strategies were identified to support sustainable management of Youtefa Bay, with *domestic waste management* emerging as the top priority (weight: 0.215). This strategy focuses on

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constructing communal waste treatment systems, developing environmentally friendly septic tanks for stilt houses, and promoting plastic waste reduction campaigns. The second priority is the *rehabilitation and conservation of mangrove ecosystems* (0.185), which involves replanting degraded areas, establishing protected zones for critical habitats, and integrating local ecological knowledge into conservation efforts. Following this is the development of an *integrated water quality monitoring system* (0.152), through the establishment of permanent monitoring stations, training of local communities in basic monitoring techniques, and the creation of a comprehensive water quality database. *Community empowerment in coastal resource management* (0.138) and *enhanced stakeholder coordination* (0.124) are also deemed crucial to ensure inclusive and cohesive implementation. Other important strategies include *managing port and transportation activities* (0.112) and *enhancing climate change adaptation* efforts (0.074). The strategy of handling domestic waste is a top priority in accordance with the results of research showing that parameters related to domestic waste are the main determining factors for the quality of the waters of Youtefa Bay. The priority of the management priority strategy based on AHP can be seen in Figure 5 below.

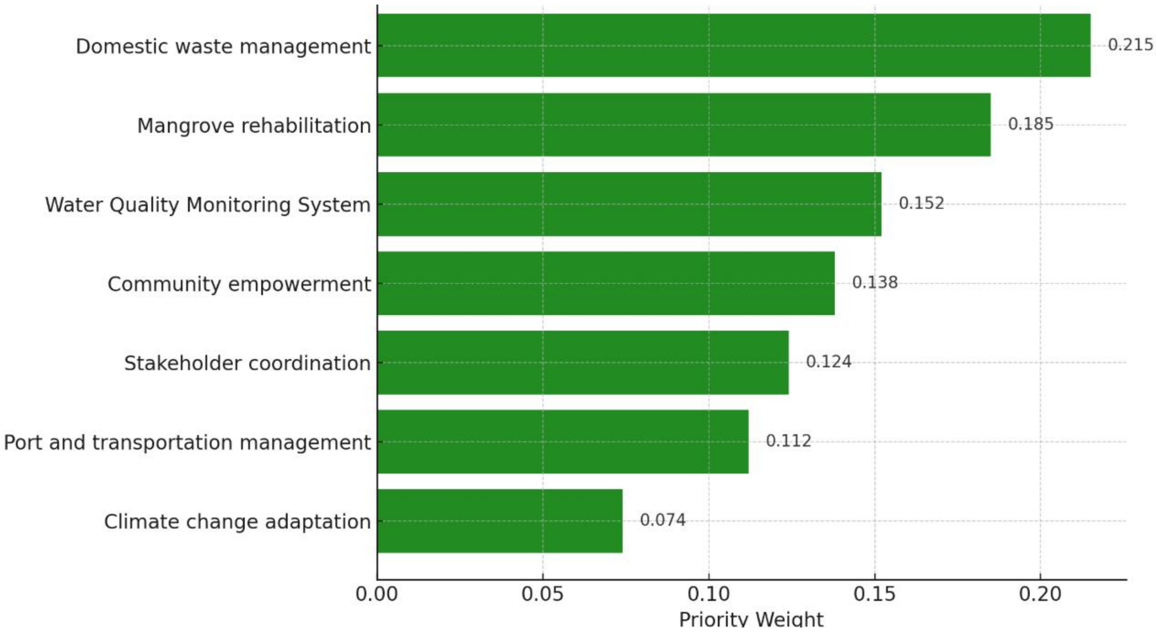

Figure 5. Priority management priority strategy based on AHP.

DISCUSSION

Youtefa Bay Water Quality Status based on CWQI

The quality status of the Youtefa Bay waters, classified as "sufficient" (CWQI = 71.24), suggests that the bay has undergone ecological stress but has not yet reached a critical level of degradation. If this "sufficient" status is not improved, ecological impacts may intensify, including eutrophication from nutrient inputs, triggering algal blooms and hypoxia from decaying matter. Significant spatial variations across study zones highlight the influence of pollution source locations on water quality, with the lowest CWQI value observed in the settlement zone (58.75), consistent with Hamuna et al. (2018), who reported the substantial impact of domestic activities on coastal waters in Papua (43). Similarly, the port zone's "less" status (62.41) is primarily attributed to high concentrations of heavy metals, aligning with the findings of Yusrizal et al (2024) (37) who documented metal accumulation in sediments of the harbor area. Temporal fluctuations, marked by lower water quality during the rainy season, further support regional observations of seasonal degradation of coastal waters in eastern Indonesia.

The Main Determining Factors For The Quality Of The Waters Of Youtefa Bay

Eutrophication-related parameters (turbidity, TSS, BOD_5, nitrate, phosphate) as the main determining factor (43.65% variance) showed the dominance of the influence of organic waste and nutrients from anthropogenic activities. This finding is in line with the research of Fianko JR (2009) (38) and Suresh K et al (2023) (39) who found similar parameters as main contributors to coastal water quality

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degradation in areas with high anthropogenic pressure. The prevalence of these eutrophication parameters has significant implications for the Bay's health ecosystem. Elevated nutrient levels, particularly nitrates and phosphates, create conditions conducive to harmful algal blooms, which can lead to oxygen depletion through decomposition processes when these algae die. This oxygen depletion threatens fish populations and benthic organisms, potentially triggering cascading effects throughout the food web, including reduced fishery resources that local communities depend upon. Furthermore, increased turbidity reduces light penetration necessary for photosynthesis in seagrass beds, threatening these critical nursery habitats for juvenile fish species.

The high concentration of heavy metals in the port zone (Component 2, 19.29% variance) reinforces the report of Silalahi HN (2017)(40) about heavy metal pollution in Youtefa Bay waters. Salinity variation (Component 3, 12.65% variance) influenced by rainfall and river flow supports the opinion of Gao L et al (2024) (41) and Lew S et al (2022) (42) on the effect of salinity on the distribution of biota and biogeochemical processes. High microbiological parameters (component 4, 6.82% variance) in the settlement zone are consistent with the findings Hamuna B (2018) (43) about microbiological contamination in Papua coastal waters.

Spatial and Temporal variations of Water Quality

Spatial patterns with water quality gradients from land to sea confirm that the main source of pollution comes from activities on land. Despite its proximity to more polluted zones, the central area of Youtefa Bay (Cluster 3 with stations 1,2,10,11,12) exhibits the best water quality due to favorable hydrodynamic conditions, such as the presence of intact mangrove ecosystems, and limited direct anthropogenic pressure. Effective water circulation in this zone likely enhances the dilution and dispersion of pollutants, while undisturbed mangroves act as natural biofilters, trapping sediments and absorbing excess nutrients. Additionally, the relative distance from concentrated sources of domestic and industrial pollution further protects this area from contamination, allowing it to maintain higher ecological integrity and a "High CWQI" status. This pattern is in line with the findings of Hamuna B (2018) (13) in Papua coastal waters, as well as in waters with high anthropogenic activity. Temporal variation with lower water quality in the rainy season (CWQI=62.8) compared to the dry season (CWQI=74.5) is caused by increased runoff from land carrying sediment and nutrients. This phenomenon is consistent with the report of Lan J (2024) (44) in the waters of the Yangtze River estuary, where CWQI decreased significantly in the rainy season as a consequence of increased runoff. An increase in chlorophyll-a concentration (4.8 μg/L) in the rainy season compared to the dry season (3.1 μg/L) indicates stimulation of phytoplankton growth by nutrient input, as reported by He T (2024) (45) in the tropical waters of Indonesia.

Relationship of anthropogenic activity to water quality

The strong negative correlation between population density and CWQI (r=-0.854) and the positive correlation between the percentage of mangrove cover and CWQI (r=0.765) illustrates the impact of human activities and the important role of mangrove ecosystems in maintaining water quality. These findings support the research of McDowell RW (2021) (46) about the connection between land utilization patterns and Youtefa Bay water quality. The positive correlation between mangrove cover and water quality (r=0.765) highlights the critical ecosystem services provided by mangroves in this tropical Bay. In the specific context of Youtefa Bay, mangroves likely function as natural biofilters that trap suspended solids and associated contaminants, as evidenced by the lower turbidity values (average 5.8 NTU) recorded in stations with >60% mangrove cover compared to stations with <20% cover (average 14.2 NTU). The extensive root systems of mangroves in Youtefa Bay, particularly Rhizophora species which dominate the area, effectively trap sediments that would otherwise increase turbidity and smother sensitive coral and seagrass habitats. Furthermore, the regression model results showing that each 1% increase in mangrove cover is associated with a 0.275 increase in CWQI value quantifies this relationship and aligns with Aurilia MF (2020) (47) findings on mangroves' filtering capabilities. Additionally, microbial communities associated with mangrove sediments likely facilitate nutrient cycling processes, evidenced by the significantly lower nitrate concentrations (0.14 mg/L vs. 0.37 mg/L) observed in well-preserved mangrove areas compared to degraded areas.

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Regression Model with R^2=0.842 explains the effect of population density, distance from settlements, and the percentage of mangrove cover on CWQI, confirming the importance of settlement management and mangrove conservation. The conversion of mangroves into settlements around Youtefa Bay has caused environmental degradation [46], while Aurilia MF (2020) [47] emphasize the function of mangroves as a natural filter for maintaining water quality.

Youtefa Bay Sustainable Management Strategy

The priorities of waste management (weight: 0.215) and mangrove rehabilitation (weight: 0.185) align with key water quality determinants. Domestic waste management is crucial for improving coastal water quality in populated areas. Mangrove conservation enhances water quality while supporting biodiversity and coastal resilience. Development of integrated monitoring system (weight: 0.152) prioritizes regular monitoring in high-pressure areas. Community Empowerment (weight: 0.138) and stakeholder coordination (weight: 0.124) are vital for marine protected areas management, integrating indigenous Papuan wisdom in Coastal Management. The Enggros and Tobati tribes' customary practices are essential, applying traditional knowledge through laws and taboos (sasi) for mangrove and marine resources. These practices include seasonal harvesting restrictions, sacred mangrove protection, and sustainable use enforcement, supporting ecological preservation and coastal management goals.

Study Limitations and Future Research Directions

While this study provides valuable insights into Youtefa Bay's water quality dynamics, several limitations should be acknowledged. First, despite sampling in both dry and rainy seasons, the snapshot nature of this assessment (one month in each season) may not fully capture the temporal variability throughout the year, particularly transitional periods and extreme weather events which may cause significant fluctuations in water quality. Second, while comprehensive, our parameter selection did not include emerging contaminants such as microplastics and pharmaceutical residues, which may be increasingly relevant in urbanizing coastal areas like Youtefa Bay. Additionally, there are inherent limitations to the CWQI methodology itself when applied to tropical environments like Youtefa Bay. The CWQI was originally developed for temperate waters with different baseline conditions and seasonal patterns. In tropical settings, natural background levels for certain parameters (e.g., temperature, turbidity during seasonal rains) may differ from temperate standards, potentially affecting index interpretation. Furthermore, the equal weighting of different parameters in the CWQI calculation may not accurately reflect their relative ecological importance in tropical coastal ecosystems.

Future research should address these limitations by implementing continuous monitoring stations at key locations to capture fine-scale temporal variations, expanding parameter coverage to include emerging contaminants, and potentially developing a modified CWQI specifically calibrated for tropical coastal ecosystems. Additionally, integrating traditional ecological knowledge from indigenous Papuan communities with scientific monitoring could provide historical context and enhance understanding of long-term environmental changes in Youtefa Bay. Finally, investigating the dose-response relationship between water quality parameters and ecosystem health indicators (coral health, seagrass coverage, fish community structure) would strengthen the ecological relevance of water quality assessments and management recommendations.

CONCLUSION

This research has successfully analyzed the water quality status of Youtefa Bay using the CWQI method integrated with statistical analysis and AHP, revealing a "fair" status (CWQI=71.24) for the entire Bay with significant spatial variations from "marginal" in the settlement zone (CWQI=58.75) to "good" in the central bay area (CWQI=83.42). Eutrophication parameters were identified as the main determinants of water quality (43.65% variance), with a strong negative correlation between population density and CWQI (r=-0.854) and a positive correlation between mangrove cover and CWQI (r=0.765), providing comprehensive understanding of environmental degradation dynamics and ecosystem resilience. The implications of these findings indicate that Youtefa Bay is at a critical point where without appropriate intervention, environmental degradation may continue to affect ecosystem resilience, fishery resource availability, and ultimately the socio-economic welfare of coastal communities dependent on the Bay, while

https://doi.org/10.56303/jhnresearch.v4i1.380

areas with high mangrove cover show potential for ecosystem recovery if appropriate management strategies are implemented.

Based on the identification of eutrophication parameters as the main drivers of water quality degradation (43.65% contribution from PCA) and AHP analysis results (weight: 0.215), it is recommended that local governments prioritize the development of domestic waste management infrastructure in settlements around the Bay, as well as implement intensive mangrove ecosystem rehabilitation programs involving indigenous local wisdom, supported by the development of integrated water quality monitoring systems, community empowerment programs through ecotourism and training in sustainable fisheries practices, and strengthening coordination among stakeholders. The implications of implementing these recommendations will have broad impacts on water quality restoration, biodiversity enhancement, improvement of fish stocks supporting local food security, increased coastal resilience to climate change, strengthening of ecotourism-based economies, and preservation of traditional cultural values associated with the bay ecosystem, thereby creating a sustainable coastal management model that can be replicated in other locations with similar characteristics..

FUNDING

This study is independent and did not receive any assistance from any party. Only get help in the form of sea transportation from local communities

ACKNOWLEDGMENTS

With the completion of this study, the researcher expressed his gratitude for the support and motivation and for the issuance of letters related to permits in the context of conducting research in the indigenous territory of Nafri, Jayapura city.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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