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River segmentation based on water quality index for management policy formulation: an analysis of the Enim River in South Sumatra

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ABSTRACT

This study aimed to delineate segments of the Enim River based on the Water Quality Index (WQI), using the Pollution Index (PI) as the primary method. Water quality data were collected from 14 monitoring stations between 2022 and 2024, covering several physicochemical and biological parameters. Hierarchical Cluster Analysis (HCA) was applied to classify stations based on similarities in pollution patterns. The results identified three main segments: stations with relatively good water quality, stations with fluctuating pollution levels, and stations with high pollution requiring priority attention. This approach provides a comprehensive spatial and temporal overview, supporting the development of more targeted and evidence-based river management policies. The study points to the WQI as an effective and accessible tool for assessing water quality, enhancing stakeholder understanding, and serving as a foundation for river conservation and restoration planning.

Keywords: cluster analysis, pollutant index, river zoning, river management, water quality index

INTRODUCTION

A river is a natural surface water flow that extends from upstream to downstream through channels or valleys (Alexander & Cooper, 2024). Rivers play a vital role in sustaining organism life cycles and maintaining ecosystem integrity. River water is widely used for domestic needs, agricultural irrigation, and as a primary drinking water source (Denny et al., 2025). In the Muara Enim region, the Enim River is one of the most important rivers in both the ecological and social landscape of Muara Enim Regency. This river not only holds historical value but also plays a significant role in supporting environmental sustainability and the economic activities of the local community.

The Enim River flows through several sub-districts, including Semendo Darat Laut, Semendo Darat Tengah, Semendo Darat Ulu, Tanjung Agung, Lawang Kidul, and Muara Enim, underscoring its role as a vital corridor that supports the livelihoods of communities along its course. The Enim River, extending 19 km with a watershed area of 39 km², serves as a vital water source for the community and plays a crucial role in maintaining local ecosystem balance. The upstream of the Enim River originates from Gemuhak Lake in Semendo Darat Ulu District and flows into the Lematang River, reflecting the region's hydrological connectivity and ecosystem diversity (Sinaga et al., 2024). Considering that it is an open water resource, the Enim River is at risk from the entry of wastewater from human activities in the surrounding area, which can harm both its ecological condition and its water quality (Utami et al., 2024). Human activities, including coal mining, coal-fired power plants, palm oil and rubber processing factories, residential settlements, and small-scale industries, predominantly influence the Enim River corridor. These activities significantly affect the river's water quality, sediment load, and overall ecosystem health, highlighting the need for integrated environmental management along the river basin.

The management of the Enim River has depended chiefly on a consistent approach over the entire course from upstream to downstream. Although monitoring data reveal considerable differences in water quality indices across several stations, no specific management measures have been implemented to maintain river health based on these variations. Management policy-making should offer a new approach for policymakers in setting priorities for managing river water quality by prioritizing three things: the difference in parameters that are the leading indicators of water quality, adjusted priority programs, the relationship between each parameter and the program, and the level of success of water quality control (Juwana et al., 2022).

The Water Quality Index (WQI), applied through the Pollution Index approach, is one of the most widely used methods for evaluating water quality (Makubura et al., 2022). This method enables the aggregation and synthesis of multiple water quality metrics into a single representative value, thereby simplifying comprehensive analysis and comparison. It serves as a practical indicator for assessing river water quality, allowing for precise classification of conditions as compliant, lightly polluted, or heavily polluted, thus supporting effective environmental management. This value also functions as a key indicator, providing an integrated assessment of the river's water quality to guide strategic management actions and decision-making (Ewaid et al., 2020). WQI is generally employed to calculate and present data for measuring river water quality (Othman et al., 2020).

This study aims to delineate segments of the Enim River based on Water Quality Indeks (WQI) values, providing a systematic and comprehensive assessment of river water quality. By integrating diverse parameters into a unified index, the study provides a scientific foundation for developing policies, planning management actions, and evaluating the outcomes of conservation efforts in the Enim River.

MATERIALS AND METHODS

Study Area

This study utilizes monitoring data from 14 stations along the Enim River, as reported in the Environmental Management Performance Information Report of Muara Enim Regency (2022–2024), covering locations such as Indramayu, Pandan Dulang, Lebak Budi, Tanjung Agung, Darmo, The Rumah Makan Kartika area, PDAM Tanjung Enim intake, PTBA Bridge, downstream of Pasar Tanjung Enim, Lingga Djaja, PLTU, Karang Raja, PDAM Muara Enim intake, and the area behind Kopi Bintang (Figure 1).

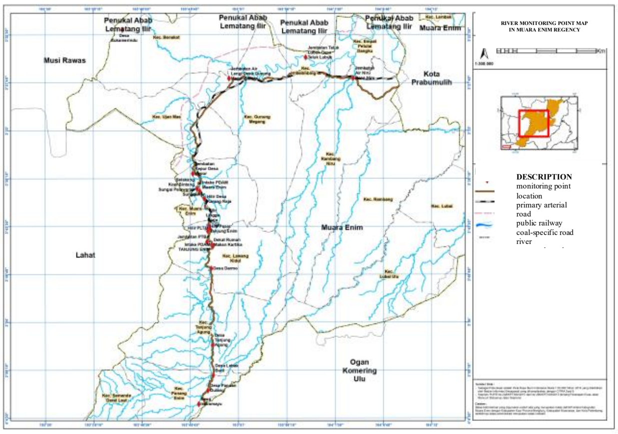

Figure 1. Sampling station for monitoring and study area

Research Data

Water quality data from 14 monitoring stations along the Enim River were collected over the past three years, with sampling conducted three times per year. Each sampling event represented different seasonal conditions: the rainy season, the transitional season, and the dry season. In 2022 and 2023, samples were collected in February, May, and June, while in 2024, sampling occurred in February, June, and August.

Each station generates nine data points (W1–W9) that reflect temporal variations in water quality conditions. The parameters that serve as the basis for the Water Quality Index (WQI) calculation include physical-chemical factors such as turbidity, electrical conductivity, pH, dissolved oxygen, nitrates, nitrites, biological oxygen demand (BOD), and chemical oxygen demand (COD) (Rubio-Arias et al., 2012; Malek et al., 2022). Biological parameters include fecal coliform and bacteriological levels (Singh & Hussian, 2016). The selection of these parameters was based on the specific characteristics of the water body and the intended purposes for its use (Das Kangabam et al., 2017; Kouadri et al., 2021). The parameters utilized for calculating the Pollution Index in this study consist of pH, biological oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), nitrate nitrogen (NO_3–N), ammonia nitrogen (NH_3–N), copper, zinc, total phosphorus (TP), and fecal coliform.

Pollution Index (PI)

The Pollution Index (PI) is calculated using a formula set by the Decree of the Minister of Environment of the Republic of Indonesia Number 115 of 2003 (Equation 1).

$$PI = \max\left(\frac{C_i}{L_{ij}}\right) \; atau \; PI = \sqrt{\frac{\sum_{j=1}^{n}\left(\frac{C_i}{L_{ij}}\right)^2}{n}} \text{...........(1)}$$

In this case, the concentration of the water quality parameter (i) is represented by L_{ij}, according to the quality standard (j). C_i, on the other hand, stands for the concentration of the water quality parameter (i) as determined by examining water samples collected at Enim River sampling stations. The Pollution Index values are then classified into various water quality ranges, as outlined in Table 1.

Table 1. Categorizes the status of water quality as per the pollution index method

Pollution Index (PI)	Level of Pollution
0 ≤ IP ≤1.0	Good
1.0 < IP	Lightly polluted
5.0 < IP ≤ 10	Moderately pollutes
IP > 10.0	Severely polluted

Statistical Analysis

Statistical Analysis and *Clustering*, and *Line Chart Average per Cluster.*

RESULTS

Pollutant Index (PI)

The analysis presented an overview of surface water quality based on assessments conducted using the Pollution Index (PI) method (Table 2).

Table 2. Results of Pollutant Index Measurements in 2025

Sampling station	W1	W2	W3	W4	W5	W6	W7	W8	W9
1	0.8	0.9	2.2	0.7	2.8	0.8	0.8	0.9	2.2
2	1.2	1.4	2.3	0.9	1.1	0.8	0.9	2.3	2.3
3	0.7	1.1	1.0	1.7	1.4	2.2	1.6	2.2	2.0
4	2.2	3.6	2.0	0.8	1.8	1.5	0.9	2.4	2.2
5	0.7	2.0	3.2	0.8	1.5	0.8	0.8	1.9	2.2
6	0.8	0.9	1.9	1.4	1.0	0.8	1.1	1.7	2.1
7	1.8	1.6	1.9	1.5	1.3	0.8	1.0	1.5	1.8
8	0.9	1.1	4.2	1.3	1.4	1.0	1.0	1.5	1.1
9	0.8	1.1	4.0	0.8	1.2	1.1	1.0	1.5	1.1
10	0.9	1.0	3.3	2.1	2.5	0.9	1.2	1.2	0.9
11	4.6	0.9	3.3	1.5	2.5	1.2	1.2	1.8	1.3
12	1.1	1.2	1.9	2.7	2.7	1.0	1.2	2.1	1.0
13	1.1	8.1	2.5	1.5	2.6	1.0	1.4	2.0	1.0
14	1.1	0.9	2.5	0.8	2.7	8.1	1.1	2.1	8.1

Note: W1-W9: IP Bulan Februari 2022 - Agustus 2024

A descriptive statistical analysis of the data in Table 3 is presented in Table 4.

Table 3. Descriptive statistics of pollutant index average data

	W1	W2	W3	W4	W5	W6	W7	W8	W9
Count	14	14	14	14	14	14	14	14	14
Mean	1.3	1.8	2.6	1.3	1.9	1.6	1.1	1.8	2.1
Std	1.0	1.9	0.9	0.6	0.7	1.9	0.2	0.4	1.8
Min	0.7	0.9	1.0	0.7	1.0	0.8	0.8	0.9	0.9
25%	0.8	1.0	1.9	0.8	1.3	0.8	0.9	1.5	1.1
50%	1.0	1.1	2.4	1.4	1.6	1.0	1.0	1.9	1.9
75%	1.2	1.6	3.3	1.5	2.6	1.2	1.2	2.1	2.2
Max	4.6	8.1	4.2	2.7	2.8	8.1	1.6	2.4	8.1

Table 4. Cluster of sampling stations

Cluster	Sampling Station
1	['S1', 'S2', 'S3', 'S4', 'S5', 'S6', 'S7', 'S8', 'S9', 'S10', 'S11', 'S12']
2	['S13']
3	['S14']

The Pollution Index (PI) results revealed spatial and temporal variations in the Enim River's water quality during nine observation periods (2022–2024), with values ranging from 0.73 to 8.12, indicating conditions from good to moderately polluted. Mean PI values of 1.32–2.60 across stations classified most sites as lightly polluted. The Pollutant Index emphasized the level of pollution of water sources by assessing the concentration of pollutants and their potential impact on the environment and human health (Bouchareb et al., 2025; Noor et al., 2023). This fluctuation in IP signifieddisparities in the degree of anthropogenic pressure throughout the river's flow.

Clustering Analysis

Cluster analysis (CA) was a multivariate statistical method aimed at discerning the grouping structure of items based on the similarity of their characteristics. This technique was utilized on data that undergone Z-score standardization, facilitating comparisons between variables in homogeneous units (Radiarta & Erlania, 2015; Dalmaijer et al., 2022). The results of the Dendrogram analysis showed the hierarchical relationships sbetween stations based on the similarity of pollution index patterns (Figure 2). The closer the distance between branches at stations, the more similar their pollution index patterns. Cutting the dendrogram at a certain level resulted in 3 main segments (segment 1, 2, and 3). The members of each cluster are presented in Table 4.

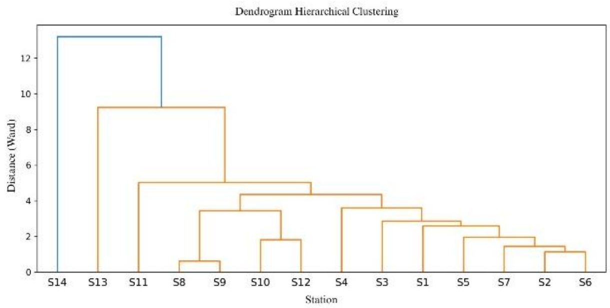

Figure 2. Hierarchical dendrogram for each station

Cluster analysis indicated that Segment 1, characterized by low-to-moderate IP values, reflected relatively good water quality. In contrast, Segment 2 exhibited sharp fluctuations during specific periods, suggesting the influence of seasonal or incidental pollution sources. Segment 3 consistently displayed high IP values, indicating a significant and persistent dominance of pollution.

Line Chart

The line graph shows the pattern of change in the average Pollutant Index for each cluster over nine measurement periods (W1–W9). Cluster 1 tended to be stable with low to moderate index values, reflecting relatively better water quality conditions. Cluster 2 showed some sharp spikes at certain times, indicating fluctuating pollution. Meanwhile, Cluster 3 consistently had a higher average value compared to the other clusters, indicating that stations in this group are relatively more polluted (Figure 3).

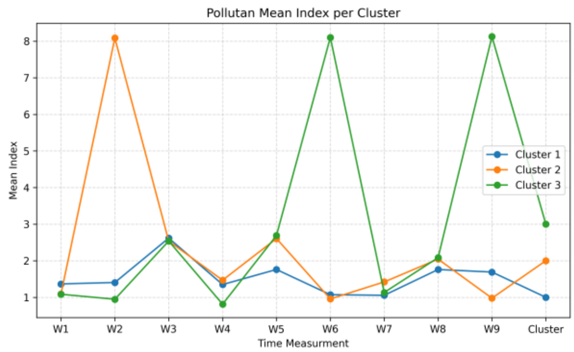

Figure 3. Pollutan mean index per cluster

Pollutant Heatmap Index

The heatmap analysis of the pollutant index per station was used to illustrate the distribution of index values across the nine measurement periods. Dark or red colors represent higher index values, indicating more severe pollution levels. The visualization results showed significant variation between stations, with some stations exhibiting much higher values than others (Figure 4). Heatmap regression is a widely used method for deep learning-based landmark localization, including facial landmark detection and human pose estimation (Yu & Tao, 2022).

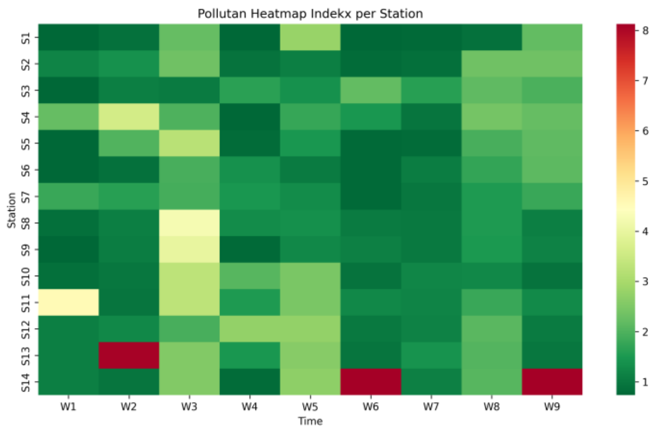

Figure 4. Pollutan heatmap index

Heatmap Ordered by Cluster

The heatmap sorted by cluster (Figure 5) shows a more structured pollution pattern, where stations within the same cluster tend to exhibit similar temporal patterns. Cluster 1 (low-medium) is characterized by stations with relatively better water quality. Cluster 2 (fluctuating) showed an unstable pattern, likely influenced by seasonal or incidental activities. Meanwhile, Cluster 3 (high) consisted of stations with dominant pollution levels, requiring priority attention in management.

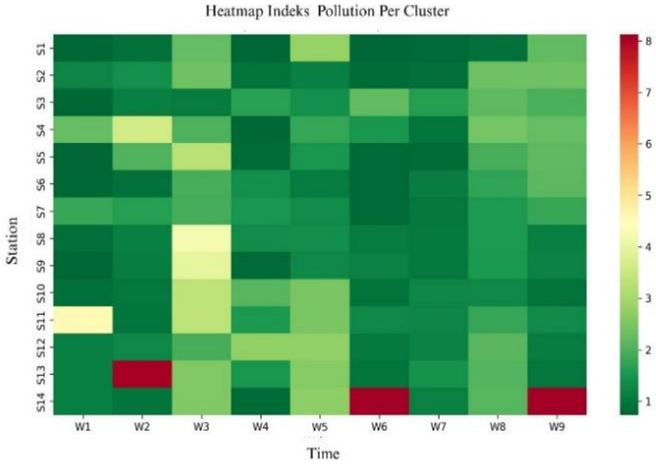

Figure 5. The heatmap sorted by cluster

DISCUSSION

The research results indicate that the water quality of the Enim River varies spatially and temporally, with the Pollution Index (PI) ranging from good to moderately polluted conditions. Overall, the average dPI value at most stations fell within the lightly polluted category, although some stations, particularly in the downstream segment, experienced significant peaks, reaching the moderately polluted category (Rubio-Arias et al., 2012). These variations showed that anthropogenic pressure from industrial activity, coal mining, and community waste contributes differently to each river segment (Chabuk et al., 2020; Sharma & Kansal, 2011; Wisha et al., 2025a, 2025b). This finding aligned with Utami et al., (2024) reported the degradation of Enim River water quality due to mining and industrial activities in Muara Enim.

Visualization through dendrograms (Figure 1), line charts, and heatmaps showed that stations in Segment 1 (S1–S12) could be used as a baseline with relatively good conditions, while S13 and S14 required special attention as locations prone to pollution. This interpretation coincided with the literature emphasizing the importance of a spatial-temporal approach in water quality assessment to support conservation and restoration strategies (Lkr et al., 2020).

Hierarchical cluster analysis successfully grouped the monitoring stations into three main segments. Segment 1 was characterized by relatively stable water quality with low to moderate IP values, making it a potential baseline for a well-preserved ecosystem. Segment 2 showed sharp fluctuations in IP values during certain periods, indicating the presence of seasonal pollutants such as mine runoff during the rainy season or increased factory production activity. Meanwhile, Segment 3 consistently recorded high IP values, reflecting continuous pollutant accumulation. This finding aligns with the study by Widyasari et al. (2023) on the Tukad Pakerisan River in Bali, which showed that pollution in the downstream section of the river tends to be more severe due to the accumulation of various pollutant sources from upstream.

From an ecological perspective, the generally lightly polluted condition of the Enim River indicated a long-term decline in the river's carrying capacity. Increased pollutant loads had the potential to accelerate eutrophication, lower dissolved oxygen levels, and disrupt the diversity of aquatic biota. This finding aligned with Dippong et al. (2022), who confirmed that the accumulation of heavy metals and excess nutrients in freshwater ecosystems can have serious impacts on benthic organisms and water resource quality (Verma et al., 2020). Water quality segmentation gave an overview of geographical priorities essential for effective pollution management (Rizkilah et al., 2024). This grouping method allowed for more targeted policy formulation, such as determining priority intervention points or region-based mitigation strategies.

These findings confirmed the importance of a spatial-temporal approach in water quality assessment. Segmentation based on the Water Quality Index (WQI) and Pollutant Index allowed for more targeted river management, for example, by prioritizing interventions in Segment 3, which consistently has a high IP, and implementing prevention in Segment 2 to anticipate seasonal surges. This approach proved more effective than the uniform upstream-to-downstream policy that is still commonly implemented (Juwana et al., 2022; Verma et al., 2020).

The use of the Water Quality Index (WQI) based on the Pollution Index (IP) proved to be simple yet communicative, as it condenses complex information into a single index that is easily understood by stakeholders (Ewaid et al., 2020; Bouchareb et al., 2025). The segmentation of water quality in the Enim River provided a foundation for evidence-based policy, focusing on conservation in Segment 1, stricter monitoring in Segment 2, and restoration efforts in Segment 3. This approach is not only applicable to the Enim River but also relevant for other rivers with similar ecological characteristics and anthropogenic pressures, in line with the principles of sustainable water resource management (Jung et al., 2025). Furthermore, the results of this research could serve as an educational tool to increase public awareness about water quality issues and the importance of river conservation, encouraging community involvement in restoration efforts (Akter et al., 2016; Othman et al., 2020).

CONCLUSION

The results of this study indicate that the combination of the Pollutant Index (PI) and hierarchical cluster analysis is capable of spatially and temporally identifying three main segments of the Enim River's water quality. Segment 1 (S1–S12) is characterized by relatively good quality, Segment 2 (S13) shows a fluctuating pollution pattern, while Segment 3 (S14) consistently has high pollution levels. These findings confirm significant differences between segments, which can serve as the basis for setting management priorities, ranging from conservation to restoration and pollution prevention. Furthermore, the use of IKA has been proven to simplify complex water quality parameters into information that is communicative for stakeholders. Thus, this research not only describes the condition of the Enim River but also provides an applicable framework for evidence-based policy formulation in river ecosystems with similar characteristics.

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