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Water Quality Measurement in Illegal Gold Mining Areas Using Sentinel-2A MSI Satellite Images of the Batanghari River, Tebo Tengah District

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Abstract. Water quality in Indonesian rivers has declined due to pollution from solid and liquid waste from industrial and domestic sources. The Batanghari River, the longest river on the island of Sumatra, faces various environmental problems, including pollution from illegal mining activities. Artisanal and small-scale gold mining (ASGM) contributes to mercury release, contaminating water and soil and posing health risks to communities. Conventional monitoring methods have limitations in coverage and efficiency. Therefore, this study utilizes Sentinel-2A MSI satellite imagery to assess and map water quality conditions around illegal gold mining areas along the Batanghari River in Tebo Tengah District. The developed model uses K- Means, Fuzzy C-Means (FCM), Principal Component Analysis (PCA), and Weighted Arithmetic Water Quality Index (WAWQI) to extract water quality features. The findings indicate that WAWQI provides a more representative quantitative assessment, revealing that areas near illegal gold mining sites in Batanghari river exhibit moderately to heavily polluted water quality. This approach is expected to support water quality monitoring and assist policymakers in managing water resources and the environment.

Keyword: Batanghari River, Clustering, Mining, Sentinel-2A MSI, WAWQI.

1. Introduction

The Batanghari River is the longest river on the island of Sumatra. It flows through the city and regency of Jambi Province, West Sumatra Province, and Riau Province. The river is 870 kilometers long, with a width of 300–500 meters and a depth of 6–7 meters [1]. To date, the Batanghari River has faced various issues, including bank erosion caused by settlements, critical land conditions, accumulated waste, and water pollution resulting from illegal logging and gold mining, which have damaged the Batanghari River's ecosystem. This is evident from the declining Water Quality Index (WQI) of Jambi Province in 2023, which stood at 46.06, making it the third lowest WQI in Indonesia after Yogyakarta Province and Jakarta [2]. However, this WQI value is aggregate and thus unable to accurately represent the water quality conditions at specific points within the region.

One of the points in the sustainable development goals for the environmental sector is to ensure that communities achieve universal access to clean water and sanitation [3]. According to SDGs target 6.3, by 2030, countries are expected to improve water quality by reducing pollution, eliminating discharges, and minimizing the release of hazardous materials and chemicals; reduce by half the proportion of untreated wastewater; and significantly increase recycling and the global reuse of recycled products [4]. Despite these global commitments ,the number of river basins (DAS) in critical condition in Indonesia continues to increase over time. The degradation of watershed areas has led to recurring environmental disasters such as floods, landslides, and droughts. Moreover,water pollution and water resources have reached levels that threaten human health and other living beings [5]. Therefore, continuous water quality monitoring is essential to detect changes and prevent further impacts on human health and ecosystems. However, one of the biggest challenges in water quality monitoring is the vast area affected and the limited availability of measurement tools. Conventionally, in situ measurements can produce accurate water quality variables through specific sampling points. However, this method is time-consuming, labor-intensive, and costly and is not suitable for large-scale monitoring [6]. This has led to the use of remote sensing as an alternative to address these issues.

In a study on water quality estimation using Sentinel-2 and Landsat 8 satellite imagery, it was found that both sensors performed well in creating multiple regression models for three optically active components. However, Sentinel-2 yielded superior results due to its Multi-Spectral Index (MSI) having more bands and finer spectral resolution compared to Landsat 8 [7].

Using this technology, researchers can measure and map water quality and identify sources of pollution more accurately. This study aims to map water quality around mining areas using Sentinel-2A MSI satellite imagery to support environmental management and restoration. These efforts are important, not only to maintain water quality but also to protect the welfare of communities living in pollution-prone areas.

2. Research Method

This research uses the Cross-Industry Standard Process for Data Mining (CRISP-DM) method. CRISP-DM consists of six stages: business understanding, data understanding, data preparation, modeling, evaluation, and deployment [8].

2.1. Business Understanding

The main problem of this study is the limitation of conventional methods in comprehensively monitoring water quality, particularly in areas affected by illegal gold mining in the Batanghari River, Jambi Province. Data from the Ministry of Environment and Forestry (KLHK, 2023) indicates that the Water Quality Index (WQI) for Jambi Province is 46.06, ranking it third from the bottom nationally.

2.2. Data Understanding

Water pollution conditions can be indicated through several variables, such as physical, chemical, and biological variables. The variables observed in this study include Chlorophyll-a [9], Electrical Conductivity (EC) [10], pH [11], Total Dissolved Solids (TDS) [12], and Total Suspended Solids (TSS) [13].

2.3. Data Preparation

2.3.1 Cloud detection. Cloud cover assessment filters useful data based on cloud cover levels in images, thereby improving data storage and transmission efficiency. Cloud mask is an important product of optical satellite image preprocessing that can help maximize the use of cloud-free image areas and improve image usability, especially in areas that are often cloudy and rainy [14].

2.3.2 Riverbank extraction. The extraction process was conducted using the same data collection period, from January 1, 2024, to December 31, 2024. The study area includes the illegal gold mining area along the Batanghari River and its surrounding areas within a 1 km radius of the river. The extraction results are raster images that will be used in the subsequent analysis stage. After the images are processed, they are used to obtain surface reflectance values (light that reflected by the Earth's surface) at the same locations as the water sampling points in the field. This reflectance is important information for water quality analysis.

2.3.3 Calculating water quality variables. The extracted raster data were then entered into QGIS software for further processing. This processing aimed to calculate the values of Chlorophyll-a (Chl-a), Electrical Conductivity (EC), pH, Total Dissolved Solids (TDS), and Total Suspended Solids (TSS). Each variable is calculated based on the combination of bands corresponding to the formula of each index from the Sentinel-2A MSI image. Table 1 shows the index formulas used.

Table 1. Water quality variable formulas.

Variable	Formula	
Chl-a	$54.658 + 520.451 \times Blue - 1221.89 \times Green + 611.115 \times Red - 198.199 \times NIR$	(1)
EC	$241.500 + 529.504 \times \left(\frac{NIR}{Aerosols}\right)$	(2)
pH	$8.790 + (1.141 \times R_6) - \left(0.288 \times \frac{Green}{Red}\right)$	(3)
TDS	$120.750 + 264.752 \times \left(\frac{NIR}{Aerosols}\right)$	(4)
TSS	$2950 \times Red\ edge\ 3^{1.357}$	(5)

2.3.4 Zonal statistics calculation. The raster data obtained will be divided into a 20 m × 20 m grid. Data modeling is performed based on the grid. Zonal statistics calculation is performed, which is a technique used to calculate statistical values from raster data in each zone or area. Zonal statistics calculation is performed using the zonal statistics feature available in the QGIS software.

2.4. Modeling

2.4.1 Water quality calculation using machine learning. The results of variable calculations from zonal statistics are used in machine learning modeling with the K-Means and Fuzzy C-Means (FCM) algorithms. This analysis was conducted using two approaches, namely Principal Component Analysis (PCA) and equal weight. K-Means is a clustering method that groups data based on the distance to the cluster center [15], while FCM is a fuzzy-based clustering method that minimizes the objective function in the grouping process [16]. The PCA method is easy to use, accurate, and widely applied in remote sensing prospecting, both nationally and internationally [17].

2.4.2 Calculating Weighted Aritmethic Water Quality Index (WAWQI). Each variable is assigned a weight according to its importance to water quality, so that the final index value reflects the overall water condition [18]. Table 2 shows the WAWQI index categories, which are divided into 5 categories [19]. The formula used to calculate the WAWQI index is shown in Equation (6) [20]. (Wi) represents the relative weight of the variables, and (Qi) represents the quality value of each variable.

$$WAWQI = \frac{\sum (W_i \cdot Q_i)}{\sum W_i} \quad (6)$$

Table 2. Categories of Weighted Arithmetic Water Quality Index (WAWQI).

WAWQI Value	Water Quality
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
>100	Unsuitable

Table 3. Water Quality Standards.

Variable	Quality Standard	Unit
Chlorophyll-a	0.04	(mg/L)
Electrical Conductivity	300	(µS/cm)
pH	8.5	
Total Dissolved Solids	1000	(mg/L)
Total Suspended Solids	50	(mg/L)

In this study, the water quality standards for river water in table 3 for the variables pH, TDS, and TSS refer to Government Regulation of the Republic of Indonesia Number 22 of 2021 concerning the Implementation of Environmental Protection and Management, specifically Annex VI, which contains water quality standards. This study uses Class II water quality standards. Class II is applicable for water recreational facilities or infrastructure, freshwater fish farming, livestock farming, irrigation for crops, and other uses requiring equivalent quality. Meanwhile, for the variables Chl-a and EC, the quality standards were obtained from scientific literature [20], which sets the threshold values for Chl- a at 0.04 mg/L and EC at 300 µS/cm.

2.5. Evaluation

2.5.1 Evaluation of the K-Means dan FCM methods. The K-Means method was evaluated using the Davies-Bouldin Index [21], Silhouette Score [21], Calinski-Harabasz Index [21], Within-Cluster Sum of Squares (WSS / Cohesion) [22], and Gap Statistics [22]. Meanwhile, Fuzzy C-Means was evaluated using the Partition Coefficient (PC) [23], Partition Entropy (PE) [23], Xie-Beni Index (XB) [23], WL Index [23], and Fuzzy Silhouette Index (FSI) [24].

2.5.2 Visualization. After obtaining the best clusters based on the evaluation results, the next step is to create a clustering map using QGIS for both methods, namely K-Means and Fuzzy C-Means (FCM), as well as a map for the WAWQI method. This map aims to visualize the results of regional grouping based on the analyzed variables.

2.5.3 Ground Truth. The ground truth for this study was obtained from Google Earth Engine by selecting locations that represent the spatial characteristics of each water quality grid. The river area was enlarged to 220 x 220 meters to provide spatial context, then marked with 20-meter grids × 20 meters according to water quality categories (Excellent to Unsuitable). Land and river separation was performed using the Modified Normalized Difference Water Index (MNDWI) with a threshold of 0.2, where positive values indicate water and negative values indicate land or vegetation [25].

3. Result and Discussion

Most existing studies still use an aggregate approach at the administrative region or watershed level, without considering the detailed spatial distribution of water quality parameters. This study uses several variables that are the same as those used in the [26] study for the variables CHL-A, EC, pH, and TDS. However, this study uses a grid-based approach that examines water quality in a spatial size of 20 × 20 meters, which is still rarely applied in water quality measurements in the Batanghari River. This study uses machine learning techniques, namely K-means and FCM, with evaluation methods referring to studies [22] and [23]. WAWQI research has been conducted on the Tigris River but using Landsat-9 imagery [20], while this study uses Sentinel-2A MSI imagery. By utilizing Sentinel-2A MSI satellite imagery and integrating machine learning techniques, water quality can be mapped comprehensively in grid form, resulting in much more detailed and representative information. The water quality calculation methods used in this study are K-Means and Fuzzy C-Means (FCM). Both methods utilize Principal Component Analysis (PCA) and equal weighting.

3.1 K-Means Method

Table 4. Evaluation of the K-Means Method Using PCA.

k	DBI	Silhouette Score	CHI	WSS	Gap Statistics
2	0.56	0.59	310467.53	183655.74	1.31
3	0.64	0.51	335128.93	101062.56	1.64
4	0.69	0.46	349720.43	68580.38	1.74
5	0.73	0.43	357349.90	51854.53	1.73

Table 5. Evaluation of the K-Means Method Using Equal Weighting.

k	DBI	Silhouette Score	CHI	WSS	Gap Statistics
2	0.61	0.56	272494.53	5813.74	1.81
3	0.74	0.46	271857.14	3472.45	2.21
4	0.83	0.40	261588.53	2557.18	2.42
5	0.90	0.36	248996.27	2077.38	2.56

Table 4 shows that 5 clusters are the most optimal clusters based on CHI, WSS and Gap Statistics. However, table 5 shows that 2 clusters are the most optimal clusters based on DBI, Silhouette, and CHI. The PCA-based K-Means method proved to be superior to the equal weight method based on DBI, Silhouette, CHI, and Rubin Index, producing five spatial clusters of water quality. However, the cluster distribution does not fully represent the variation in water quality conditions along the river. Based on the radar chart in figure 1, Cluster 3 has relatively high average variable values and is not significantly different from Cluster 1. However, it spatially dominates the main river flow, thus failing to adequately reflect the variation in water quality characteristics.

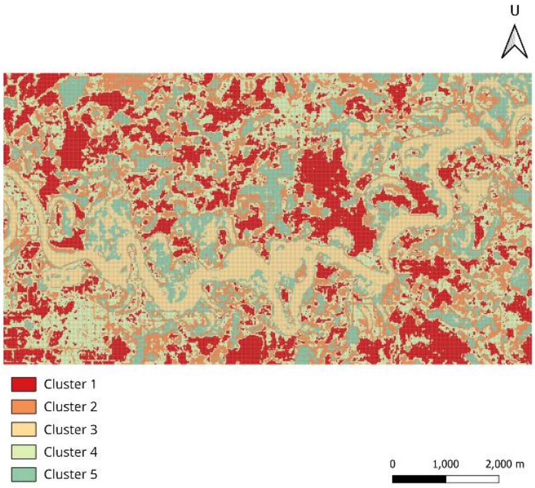


Figure 1. K-Means clustering results of the Batanghari River, Tebo Tengah District, Jambi Province.

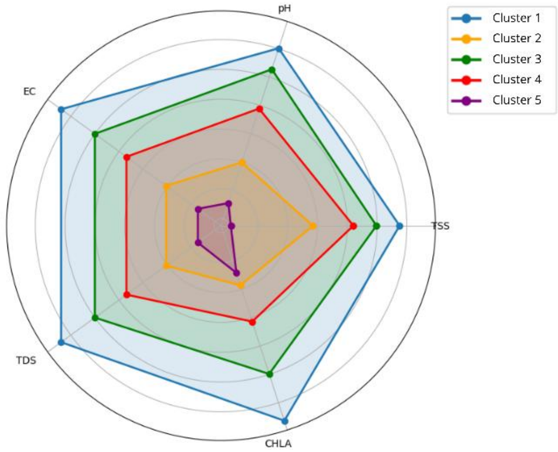


Figure 2. Radar chart of K-means clustering.

3.2 Fuzzy C-Means (FCM) Method

Based on tables 6 and 7, it can be seen that two clusters are the optimal choice because they have the best separation and a more stable cluster structure. However, PCA provides better evaluation results than the equal weight method for each variable. Figure 3 shows the results of the Fuzzy C-Means method using PCA with two clusters.

Table 6. Evaluation of the FCM Method Using PCA.

k	Partition Coefficient	Partition Entropy	Xie Beni Index	WSS	Fuzzy Silhouette Index
2	0.84	0.26	0.15	0.07	0.69
3	0.75	0.45	0.32	0.12	0.62
4	0.69	0.58	0.54	0.12	0.58
5	0.65	0.68	0.78	0.12	0.55

Table 7. Evaluation of FCM Method Using PCA.

k	Partition Coefficient	Partition Entropy	Xie Beni Index	WSS	Fuzzy Silhouette Index
2	0.83	0.29	0.17	0.08	0.67
3	0.72	0.50	0.40	0.15	0.58
4	0.64	0.67	0.73	0.16	0.52
5	0.58	0.82	1.10	0.17	0.48

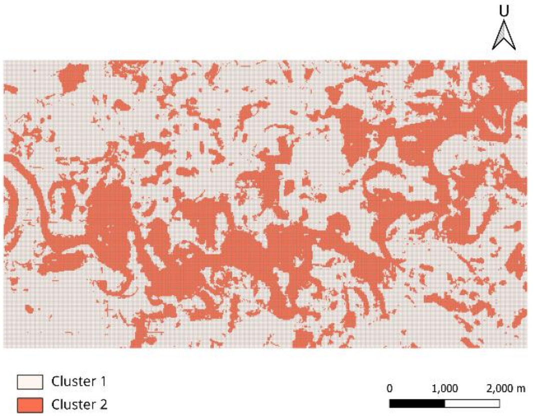


Figure 3. FCM clustering results of the Batanghari River, Tebo Tengah District, Jambi Province.

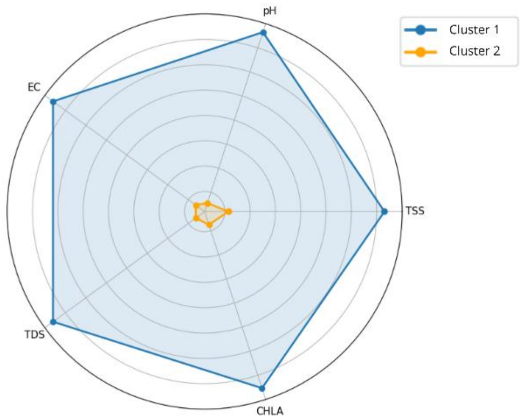
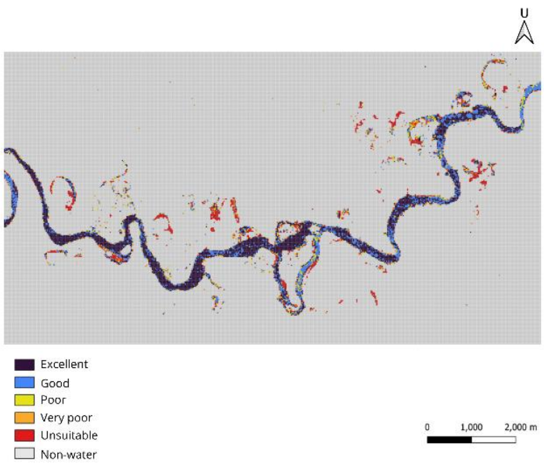


Figure 4. Radar chart of FCM clustering.

The radar chart in figure 4 shows the clustering results using FCM with two clusters. Cluster 1 shows higher values for all variables, reflecting water with higher levels of acidity, suspended solids, dissolved solids, phytoplankton activity, and dissolved salt concentration. Meanwhile, cluster 2 shows relatively low values for all variables.

3.3 Weighted Arithmetic Water Quality Index (WAWQI) Method

The WAWQI mapping in figure 5 shows that most of the Batanghari River basin is classified as Excellent and Good, indicating that water quality conditions are still relatively safe according to Class II quality standards. The Class II water quality standards of Government Regulation of the Republic of Indonesia No. 22 of 2021 are not intended for drinking water but for activities such as water recreation, freshwater fish farming, livestock farming, irrigation, and other uses equivalent. However, at several points close to illegal gold mining activities, water quality declined to the unsuitable category. These findings reflect the significant impact of anthropogenic activities on water quality in the area. The existence of areas with low water quality is an early indication of potential water degradation.



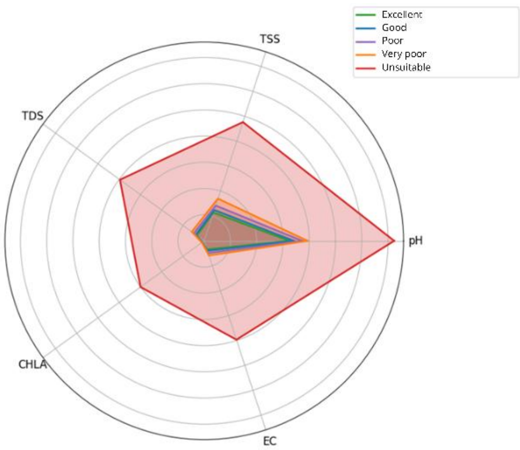


Figure 5. WAWQI mapping results of the Batanghari River, Tebo Tengah District, Jambi Province.

Figure 6. WAWQI Radar chart.

The radar chart in figure 6 shows a comparison of five water quality variables in the WAWQI category. The Excellent category has the lowest variable values, indicating minimal dissolved substances and good chemical quality. The Good category shows a slight increase in EC, TDS, and TSS with neutral to slightly alkaline pH, while CHLA remains low, so water quality is still considered good. The Poor category is characterized by a significant increase in TSS and TDS, a slight increase in EC, higher pH, and an increase in CHLA, indicating the onset of eutrophication and a decrease in water clarity. In the Very Poor category, TSS and TDS are high, EC increases, pH is high, and CHLA rises sharply, indicating high turbidity and chemical contamination. Meanwhile, the Unsuitable category has extreme values for all variables.

3.4 Ground Truth Weighted Arithmetic Water Quality Index (WAWQI)

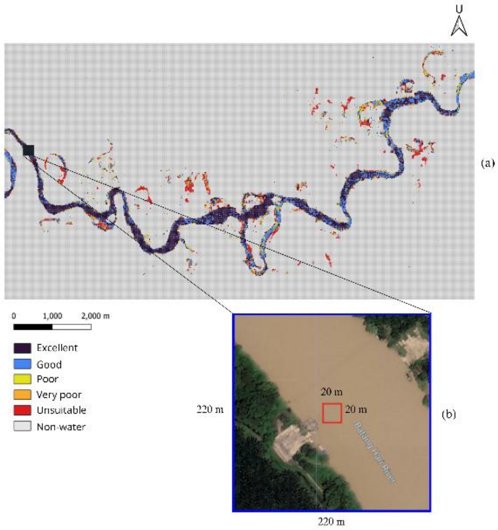


Figure 7. Ground Truth Excellent Category WAWQI.

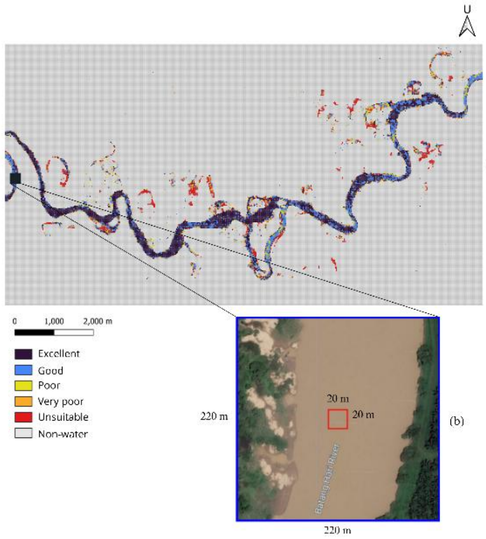


Figure 8. Ground Truth Good Category WAWQI.

The point in figure 7 is located in the main stream of the Batanghari River, geographically surrounded by dense vegetation cover and minimal anthropogenic activity in the surrounding area. The turbidity level at this point is relatively low compared to other locations. No mining activity was observed in the vicinity of this area. The " Excellent " category at this point reflects that water quality variables are close to their ideal values. This finding indicates that certain segments of the Batanghari River still have relatively well-preserved ecological conditions based on the five variables used, particularly in areas distant from anthropogenic disturbances.

Figure 8 shows the Good category point. Based on Google Earth Engine (GEE) results, the color of the water at this point is relatively uniform and not too dense. Although not as clean as the " Excellent " category, the water in this area has a moderate level of turbidity. This location is not directly adjacent to active mining pits, but there are indications of former mining pits or small pools on the southwest side. The "Good" category indicates that the WAWQI index value at this point falls within the range still suitable for Class 2.

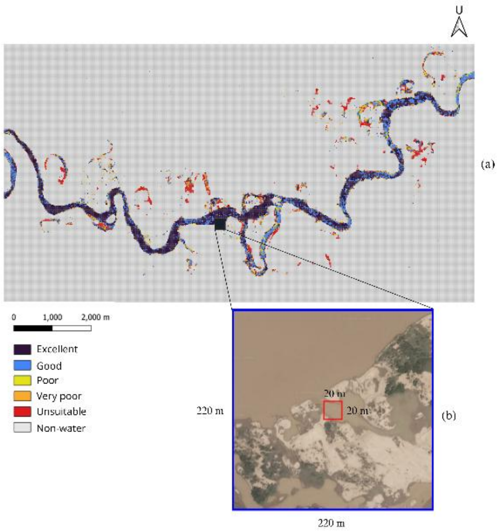


Figure 9. Ground Truth Poor Category WAWQI.

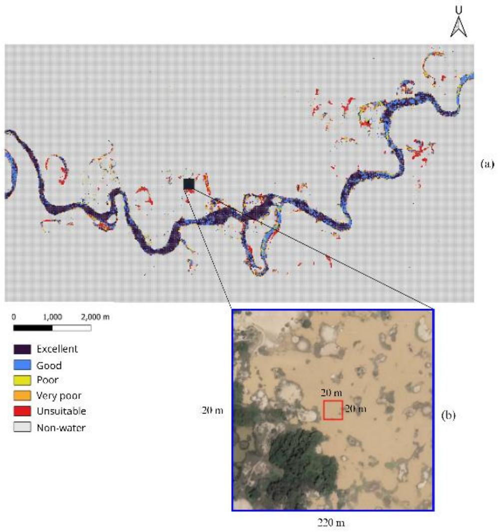


Figure 10. Ground Truth Very Poor Category WAWQI.

Figure 9 shows the poor category point. Visually, the water at this location appears more turbid than the "Good" and " Excellent " categories, with a uniform brown color indicating high TSS levels. This point is directly adjacent to land showing signs of illegal gold mining excavations. This finding reinforces that mining activities that directly interact with river bodies have the potential to significantly degrade water quality.

Figure 10 is a point in the very poor category. Visually, the area around the observation point is a former mining excavation with scattered water holes and brown, turbid water, indicating high TSS levels. This condition shows that the former mining pits are highly vulnerable to extreme water quality degradation and have the potential to become a source of pollution to the main river through runoff during the rainy season or seepage.

Figure 11 shows an area classified as unfit. This area is located outside the main river channel but remains within a zone heavily influenced by illegal gold mining activities. The site is situated in an area of former illegal gold mining pits, with the environment dominated by flooded excavation pits. The water at this location appears turbid and brown in color. These findings indicate that illegal mining activities around rivers can cause significant water quality degradation in the surrounding areas.

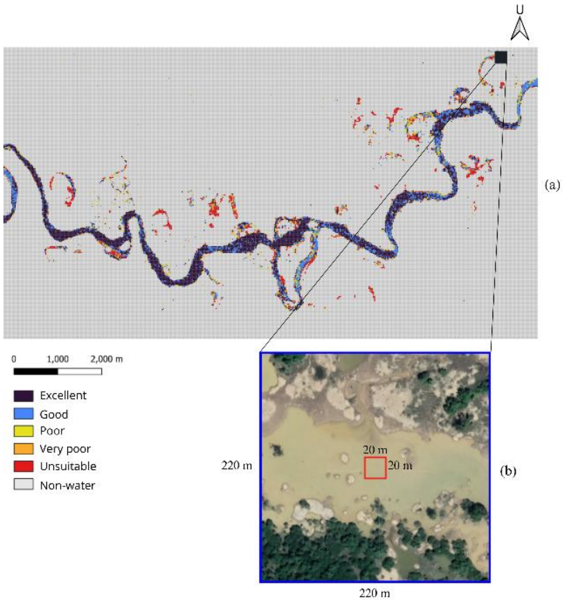


Figure 11. Ground Truth Unsuitable Category WAWQI.

4. Conclusion

This study shows that the K-Means and Fuzzy C-Means methods with PCA produce better performance than the equal weight approach. However, the clustering results are still limited in interpreting specific water quality status, so the Weighted Arithmetic Water Quality Index (WAWQI) was used, which is capable of providing a more representative quantitative assessment. Measurement results indicate that some areas, particularly those near illegal gold mining activities, fall into the moderately to heavily polluted water quality category. For future development, subsequent research could incorporate optically inactive variables to enhance the comprehensiveness of water quality representation and compare with other machine learning algorithms, such as Neural Networks, to evaluate the most optimal method for water quality data segmentation and interpretation.

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