



Preliminary Assessment of Spring Water Sources as Raw Water using the Weighted Arithmetic Water Quality Index in Batu City, Indonesia

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ABSTRACT

Assessing raw-water quality is essential for ensuring a safe drinking-water supply, particularly in municipalities that rely on natural springs. This study evaluated the physicochemical and microbiological quality of six spring-water sources supplying Perumda Air Minum Among Tirto in Batu City, Indonesia. Water samples were collected in December 2024 from Ngesong, Banyuning, Gemulo, Torong Belok, Darmi, and Kasinan. Physicochemical parameters were assessed against Indonesia's Ministry of Health Regulation No. 2 of 2023 and incorporated into the Weighted Arithmetic Water Quality Index (WAWQI) calculations, while *Escherichia coli* and total coliforms were evaluated separately. Turbidity ranged from 0.02 to 0.05 NTU, total dissolved solids from 118 to 288 mg L⁻¹, and hardness from 62 to 169 mg L⁻¹ as CaCO₃. Banyuning exhibited deviations in pH (6.46) and color (15 TCU), while Gemulo and Darmi recorded the highest nitrate concentrations (11 mg L⁻¹). All springs were classified as having excellent physicochemical water quality under the adopted WAWQI framework, with values ranging from 0.776 to 4.060. Nevertheless, total coliforms were detected in all sources (7–80 CFU/100 mL), whereas *E. coli* was only identified at Ngesong (20 CFU/100 mL) and Darmi (1 CFU/100 mL), indicates recent fecal contamination which requiring immediate disinfection prior to distribution. It is importance of combining physicochemical WAWQI assessment with independent microbiological monitoring to guide source protection and municipal raw-water management.

1. INTRODUCTION

Access to safe and reliable drinking water is essential for public health, socioeconomic development, and environmental sustainability (Li and Wu, 2019). However, maintaining water quality remains challenging due to the combined influences of natural hydrogeological processes (Tleuova et al., 2023), land-use changes (Cheng et al., 2022), agricultural activities (Sasakova et al., 2018), and anthropogenic contamination (Shrestha et al., 2023). Groundwater and natural springs are important sources of municipal drinking-water supply, particularly in mountainous regions where groundwater recharge and discharge sustain water availability (Verma and Jamwal, 2022). Although spring water is relatively protected from direct surface contamination, its quality may deteriorate due to agricultural runoff (Sasakova et al., 2018), domestic wastewater infiltration (Heinz et al., 2009), and inadequate protection of

recharge areas (Taloor et al., 2020). In volcanic terrains, unconfined aquifers may be particularly vulnerable to shallow contamination because infiltrating surface water and associated pollutants can reach groundwater through permeable geological formations. Furthermore, structural deficiencies in spring capture facilities (*brongcaptering*), such as cracks, unsealed inspection lids, and inadequate surface drainage, may provide additional pathways for contaminant ingress. These vulnerabilities highlight the importance of protecting both recharge areas and spring collection infrastructure to maintain raw-water quality. Consequently, systematic water-quality monitoring is essential for groundwater ensuring sustainable drinking-water management (Chidiac et al., 2023; Zelalem et al., 2026).

Water-quality assessment requires evaluating physicochemical and microbiological parameters, as these indicators provide complementary information about water characteristics and potential contamination (Zelalem et al.,

2026). The Water Quality Index (WQI) is widely used to simplify complex water-quality information by integrating multiple parameters into a single numerical indicator. Among the available approaches, the Weighted Arithmetic Water Quality Index (WAWQI) provides a straightforward method for evaluating physicochemical water quality based on measured concentrations, reference standards, and parameter-specific weights (Jumber et al., 2024). This approach converts individual water-quality measurements into dimensionless quality ratings and aggregates them into an overall index. Chidiac et al. (2023) identified parameter selection, sub-index transformation, weighting, and aggregation as fundamental components of WQI development. Although WAWQI facilitates comparison among sampling locations, its classifications depend on parameter selection and weighting procedures. Furthermore, an aggregated index may obscure exceedances of individual contaminants. Therefore, WAWQI should be interpreted alongside individual water-quality physicochemical parameters assessments to identify potential water-quality concerns. Furthermore, microbiological indicators, particularly *E. coli* and total coliforms, require independent evaluation because favorable physicochemical index values do not necessarily indicate microbiological safety (Zelalem et al., 2026).

Batu City, located in East Java, Indonesia, relies heavily on natural springs for its municipal water supply. The municipal drinking-water utility, Perumda Air Minum Among Tirto, utilizes spring-water sources with a combined capacity of 234 L s⁻¹ in 2024, serving more than 225,000 residents. These springs serve different distribution areas through a predominantly gravity-fed water-supply system. Although gravity-fed distribution systems reduce pumping requirements, pressure fluctuations and localized negative-pressure conditions may facilitate microbial intrusion through pipe leaks, while biofilm accumulation can contribute to bacterial persistence within distribution networks. These risks may be exacerbated by inadequate residual chlorine concentrations, highlighting the importance of effective disinfection and continuous water-quality monitoring throughout the distribution system. Furthermore, their geographical distribution and hydrogeological characteristics may contribute to differences in water quality, while surrounding land-use activities and potential contamination pathways may influence physicochemical and microbiological conditions. Batu City includes agricultural, residential, and tourism-related activities that may influence groundwater recharge areas and spring-water quality. Therefore, evaluating water quality across these sources is important for understanding spatial differences and supporting raw-water management within the municipal drinking-water supply system.

The application of WAWQI to multiple spring-water sources provides an opportunity to establish a consistent comparative assessment of physicochemical water quality (Shrestha et al., 2023). However, microbiological contamination requires independent evaluation because zero-tolerance standards for indicators such as *E. coli* cannot be directly incorporated into the conventional WAWQI calculation (Zelalem et al., 2026). Specifically, a reference standard of zero results in division by zero in the inverse-standard weighting equation ($W_i = K/S_i$) and undefined quality-rating when both the reference standard and ideal

value are zero. Therefore, microbiological parameters were evaluated separately to avoid mathematical inconsistencies and ensure that microbial contamination is not obscured by aggregated physicochemical index values. This complementary approach enables physicochemical WAWQI classifications to be interpreted alongside microbiological findings without modifying the conventional index formulation (Ibrahim et al., 2026). Such an approach is particularly relevant to municipal water utilities that rely on multiple natural springs with potentially distinct contamination characteristics.

Therefore, this study aims to assess the physicochemical quality of six spring-water sources used for municipal drinking-water supply in Batu City, Indonesia, using the Weighted Arithmetic Water Quality Index. The study evaluates selected physicochemical parameters, determines and compares WAWQI values, and classifies water-quality conditions across the investigated springs. Microbiological quality is independently assessed using *E. coli* and total coliform measurements and their compliance with applicable water-quality criteria. The findings are expected to provide a comparative characterization of spring-water quality and support source-specific monitoring, protection, and sustainable raw-water management.

2. METHOD

2.1 Study Area

The study was conducted in Batu City, East Java, Indonesia, focusing on six natural spring-water sources utilized as raw water for municipal drinking-water supply by Perumda Air Minum Among Tirto. The investigated springs comprised Ngesong, Banyuning, Gemulo, Torong Belok, Kasinan, and Darmi, which are distributed across different locations within the municipal water-supply system. The investigated springs contribute to municipal water supply through a predominantly gravity-fed distribution system.

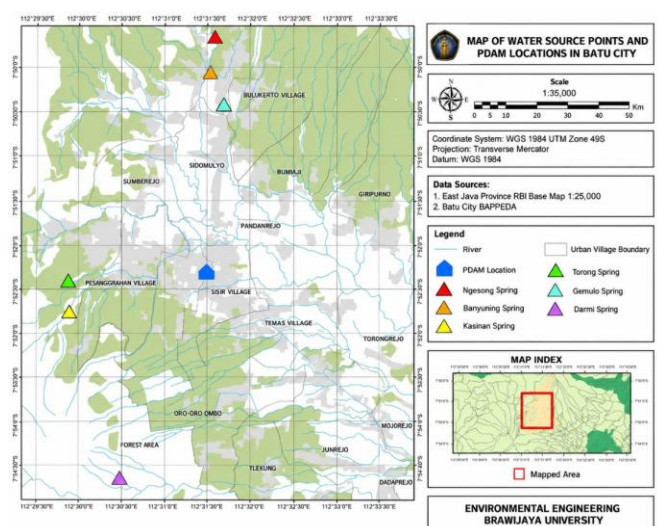


Figure 1. Map of the investigated spring-water sources in Batu City, Indonesia

The six spring sources were selected to represent the principal raw-water sources serving different municipal distribution areas. Their geographical locations and

surrounding environmental conditions may influence water-quality characteristics through variations in hydrogeological properties and potential anthropogenic activities. The geographical distribution of the sampling locations is presented in Figure 1.

2.2 Water Sampling and Sample Preparation

Water samples were collected directly from the natural emergence points of the six spring-water sources in December 2024. One water sample was collected from each spring, resulting in six samples in total. As the sampling was conducted during a single monitoring period without temporal or seasonal replication, the results represent the physicochemical and microbiological conditions observed at the time of sampling. This sampling design limits the assessment of temporal variability, particularly potential changes in water chemistry and microbial contamination associated with seasonal rainfall and groundwater recharge. Therefore, the findings should be interpreted as a preliminary characterization of the investigated spring-water sources rather than a comprehensive assessment of their long-term water quality. Further monitoring involving repeated sampling during both wet and dry seasons is necessary to evaluate seasonal variability and strengthen the representativeness of the results.

Water samples for physicochemical and microbiological analyses were collected in separate containers to prevent cross-contamination. Physicochemical samples were collected using clean polyethylene bottles, whereas microbiological samples were collected aseptically in sterile sampling containers. Samples were maintained at approximately 4 °C during transportation and analyzed within 24 hours of collection, following the procedures described in the Standard Methods for the Examination of Water and Wastewater (APHA, 23rd edition) for microbiological water-quality analysis. Field measurements of temperature, pH, and electrical conductivity were performed at the sampling sites where applicable. Following collection, samples were labeled and transported to the laboratory under appropriate preservation and temperature conditions. Sample preservation, holding times, and analytical procedures followed the applicable standard methods for water and wastewater examination.

2.3 Physicochemical Water Quality Analysis

The physicochemical characteristics of the investigated spring-water sources were evaluated using selected water-quality parameters relevant to raw water intended for clean-water production. The parameters considered included pH, temperature, total dissolved solids (TDS), hardness, nitrate, nitrite, total organic, sulfate, and other available inorganic constituents. Temperature and pH were determined using calibrated field instruments, while other parameters were analyzed using validated laboratory procedures according to the available analytical equipment and applicable standard methods. The measured physicochemical concentrations were compared with the Indonesia's Ministry of Health Regulation No. 2 of 2023 (Ministry of Health of the Republic of Indonesia, 2023). Parameters included in the WAWQI calculation were selected based on their relevance to raw-

water quality, availability of reliable analytical measurements, and compatibility with the weighting and quality-rating procedures of the selected index.

2.4 Weighted Arithmetic Water Quality Index

The WAWQI was used to assess the physicochemical quality of the investigated spring-water sources. The method integrates selected physicochemical parameters into a composite index based on their measured concentrations, reference standards, and assigned weights (Chidiac et al., 2023; Zelalem et al., 2026). The WAWQI was calculated using Equation (1):

$$WAWQI = \frac{\sum_{i=1}^n q_i W_i}{\sum_{i=1}^n W_i} \quad (1)$$

where q_i represents the quality rating of the i -th parameter, W_i is the corresponding unit weight, and n is the number of physicochemical parameters included in the assessment.

The quality rating (q_i) was determined using Equation (2):

$$q_i = \frac{V_i - V_{oi}}{S_i - V_{oi}} \times 100 \quad (2)$$

V_i represents the measured value of the i -th parameter, S_i is its corresponding reference standard, and V_{oi} represents the ideal value. Dissolved oxygen (DO) was not included in the WAWQI calculation because DO measurements were not available in the analytical dataset. Accordingly, no ideal or reference value was assigned to DO. The ideal values used in the WAWQI calculation were defined according to the characteristics of the included physicochemical parameters, with an ideal value of zero applied where appropriate and a neutral ideal value of 7.0 assigned to pH. The selection of ideal values was therefore parameter-specific rather than based on a universal assumption of zero.

For pH, the appropriate upper or lower standard boundary was selected according to the direction of deviation from the ideal value.

For pH values above 7.0:

$$q_{pH} = \frac{V_{pH} - 7.0}{S_{upper} - 7.0} \times 100 \quad (3)$$

For pH values below 7.0:

$$q_{pH} = \frac{7.0 - V_{pH}}{7.0 - S_{lower}} \times 100 \quad (4)$$

S_{upper} and S_{lower} represent the upper and lower acceptable pH limits, respectively. This formulation assigns a quality rating of zero to neutral pH and increases the rating as the measured pH approaches either regulatory boundary

The unit weight (W_i) was calculated using Equation (5):

$$W_i = \frac{K}{S_i} \quad (5)$$

K is the proportionality constant, determined using Equation (6):

$$K = \left(\sum_{i=1}^n \frac{1}{S_i} \right)^{-1} \quad (6)$$

The calculated WAWQI values were classified into five water-quality categories: excellent (0–25), good (>25–50), poor (>50–75), very poor (>75–100), and unsuitable for

drinking (>100). Lower WAWQI values indicate better physicochemical water quality. The same parameter selection, reference standards, and weighting procedures were applied consistently across all investigated spring-water sources to ensure comparability. Only physicochemical parameters were included in the WAWQI calculation. Microbiological parameters, including *E. coli* and total coliforms, were evaluated separately.

The WAWQI was calculated using a weighted aggregation approach in which the relative weight assigned to each parameter was inversely proportional to its permissible reference value. Accordingly, parameters with smaller reference values, particularly trace metals, received greater mathematical weights. For parameters with an ideal value of zero, measured concentrations recorded as zero produced zero quality ratings. These parameters contributed to the sum of weights without increasing the weighted quality-rating numerator, thereby reducing the overall WAWQI value. Consequently, the resulting index must be interpreted in conjunction with individual parameter concentrations and their respective reference limits

3. RESULTS AND DISCUSSION

3.1 Physicochemical Characteristics of Spring Water

The physicochemical characteristics of the six spring-water sources showed generally favorable conditions, with variations in dissolved mineral concentrations and selected water-quality parameters (Table 1). Temperature remained relatively uniform (23–24 °C), while turbidity ranged from 0.02 to 0.05 NTU, substantially below the reference value of 3 NTU. The remarkably low turbidity values (0.02–0.05 NTU) observed across all six springs indicate excellent water clarity and suggest effective natural attenuation of suspended particles within the groundwater system. This characteristic may be associated with groundwater filtration through volcanic deposits commonly found in the Batu City region. Such geological formations can potentially enhance particle retention during subsurface transport, contributing to the low turbidity observed at the spring outlets. Nevertheless, detailed hydrogeological investigations are required to establish the specific filtration mechanisms and geological controls. Importantly, low turbidity alone does not guarantee microbiological safety, as microbial contamination may still occur despite high water clarity.

TDS varied from 118 mg L⁻¹ at Darmi to 288 mg L⁻¹ at Banyuning, whereas total hardness ranged from 62 to 169 mg L⁻¹ as CaCO₃. Sulfate concentrations exhibited greater spatial variation (3–70 mg L⁻¹), potentially reflecting differences in groundwater mineralization and water–rock interactions. Sulfate concentrations exhibited a distinct spatial variation, with relatively higher concentrations at Ngesong, Banyuning, and Gemulo (56–70 mg/L) than at Torong Belok, Darmi, and Kasinan (3–4 mg/L). This variation may reflect differences in groundwater flow pathways, aquifer lithology, and water–rock interactions within the volcanic hydrogeological setting of Batu City. Previous studies of the Arjuno–Welirang volcanic complex have reported hydrochemical variations associated with groundwater mixing and hydrothermal processes (Harijoko et al., 2017). Similar variations in spring-water chemistry have been reported by Barakat et al. (2018), who

investigated physicochemical and microbiological characteristics of springs used for drinking-water supply in Morocco. However, the present dataset does not include major-ion composition, aquifer characteristics, or groundwater residence-time measurements sufficient to identify the dominant geochemical processes. Therefore, the observed mineral differences should be interpreted as spatial variations in water chemistry rather than direct evidence of particular geological mechanisms.

Variations in pH and color revealed localized departures from the selected reference criteria. Banyuning recorded the lowest pH (6.46), slightly below the acceptable range of 6.5–8.5. The slightly acidic pH recorded at Banyuning Spring (6.46) was marginally below the recommended range of 6.5–8.5. This condition may be influenced by dissolved CO₂ and subsequent carbonic acid formation, which can contribute to groundwater acidity in volcanic environments. However, the origin of dissolved CO₂ remains uncertain without specific hydrogeochemical evidence. Although the deviation from the recommended pH range was relatively small, it may have implications for municipal water distribution, particularly where iron-based pipes are used. Lower pH can increase the solubility of iron corrosion products and potentially contribute to metal release, discoloration, and deterioration of water quality during distribution (Zhang et al., 2021). Therefore, further assessment of alkalinity, dissolved CO₂, and corrosion potential is recommended to determine whether pH adjustment or other corrosion-control measures are necessary before distribution.

Banyuning Spring exhibited the highest color value (15 TCU), exceeding the reference value of 10 TCU, despite relatively low iron (0.03 mg/L) and manganese (0.0031 mg/L) concentrations. This suggests that dissolved metals were unlikely to be the dominant contributors to water color. Instead, the elevated colour may be associated with naturally occurring dissolved organic matter, particularly humic and fulvic substances derived from the decomposition of vegetation and organic-rich soils within the catchment. Further analyses of dissolved organic carbon (DOC), UV254 absorbance, and true versus apparent colour are required to distinguish between organic matter transported through groundwater and local contributions from surface vegetation.

Nitrate concentrations ranged from 2 to 11 mg L⁻¹, with the highest values observed at Gemulo and Darmi. Although these concentrations remained below the reported reference value of 20 mg L⁻¹, their spatial differences warrant attention. These relatively elevated concentrations may indicate additional nitrogen inputs associated with agricultural activities, fertilizer application, organic amendment, and natural nitrogen cycling may contribute nitrogen compound and influence groundwater concentrations, although their contributions cannot be established from the present measurements (Abascal et al., 2022). Previous investigations have demonstrated that nitrate contamination in groundwater is frequently associated with agricultural and residential land uses, particularly where nitrogen compounds migrate through permeable soils into aquifers (Duda et al., 2023).

Table 1. Physicochemical characteristics of the six spring-water sources in Batu City

Water Quality Parameters	S1	S2	S3	S4	S5	S6
Turbidity (NTU)	0.05	0.02	0.02	0.02	0.02	0.04
Color (TCU)	3.4	15	8	3.2	0	0
Total dissolved solids (mg L ⁻¹)	284	288	246	230	118	268
Temperature (°C)	24	23	24	24	24	24
pH	7.1	6.46	6.54	6.5	6.9	6.8
Iron (mg L ⁻¹)	<0.02	0.03	<0.02	<0.02	0.03	0.06
Fluoride (mg L ⁻¹)	0.35	0.32	0.12	0.21	<0.056	0.41
Total hardness (mg L ⁻¹ as CaCO ₃)	169	144	156	142	62	156
Manganese (mg L ⁻¹)	<0.003	0.0031	<0.003	<0.003	<0.003	<0.003
Nitrate (mg L ⁻¹)	2	2	11	3	11	2
Nitrite (mg L ⁻¹)	<0.007	<0.007	<0.007	<0.007	<0.007	<0.007
Cyanide (mg L ⁻¹)	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Detergent (mg L ⁻¹)	<0.019	<0.019	<0.019	<0.019	<0.019	<0.019
Chromium (mg L ⁻¹)	<0.006	<0.006	<0.006	<0.006	<0.006	<0.006
Zinc (mg L ⁻¹)	0.03	0.04	0.04	0.33	0.12	0.25
Sulfate (mg L ⁻¹)	56	68	70	3	4	4
Lead (mg L ⁻¹)	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Organic matter (mg L ⁻¹)	0.8	0.9	1.4	0.3	0.5	0.3

Note: S1=Ngesong, S2=Banyuning, S3=Gemulo, S4=Torong Belok, S5=Darmi, S6=Kasanan, RV=Reference value, *=reference value for temperature is the standard deviation of the temperature.

Other parameters, including iron, fluoride, manganese, zinc, and organic matter, remained below their respective detection limit. Nitrite, cyanide, detergent, chromium, and lead were reported as below 0.007, 0.002, 0.019, 0.006, 0.005, respectively. These findings indicate generally favorable physicochemical conditions, with specific concerns regarding pH and color at Banyuning. The observed differences provide the basis for comparing the six spring sources using the WAWQI, while microbiological quality requires independent assessment.

3.2 Weighted Arithmetic Water Quality Index and Water Quality Classification

The WAWQI revealed consistently excellent physicochemical water quality across the six spring-water sources supplying the municipal drinking-water system in Batu City (Figure 2). The calculated WAWQI values ranged from 0.776 to 4.060, with all investigated springs falling

within the excellent water-quality category (WAWQI = 0–25). Ngesong exhibited the lowest WAWQI value (0.776), followed by Torong Belok (1.426), Darmi (2.622), Kasanan (2.222), Gemulo (3.929), and Banyuning (4.060). Although all sources were classified within the same water-quality category, the differences in index values indicate variations in their aggregated physicochemical characteristics. Banyuning exhibited the highest WAWQI value, approximately 5.2 times that of Ngesong, suggesting a greater relative departure from the selected reference conditions. Nevertheless, these differences did not result in changes in the overall water-quality classification, indicating that the measured physicochemical characteristics remained within the excellent category under the adopted WAWQI framework.

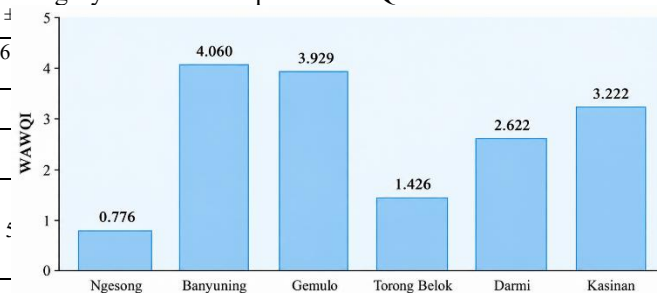


Figure 2. Weighted Arithmetic Water Quality Index values across the six spring-water sources

The variation in WAWQI values reflects differences in the measured physicochemical characteristics of the investigated spring sources (Table 1). Banyuning, which exhibited the highest WAWQI value, also recorded the highest color value (15 TCU), exceeding the reference criterion of 10 TCU, and a slightly acidic pH of 6.46, below the specified lower limit of 6.5. Gemulo, which had the second-highest WAWQI value, exhibited a nitrate concentration of 11 mg L⁻¹, compared with 2–3 mg L⁻¹ in several other sources. However, Darmi also recorded a nitrate concentration of 11 mg L⁻¹ while exhibiting a lower WAWQI value (2.622), demonstrating that the index cannot be explained by nitrate concentrations alone. The differences in WAWQI values therefore need to be interpreted in relation to the combined contributions of parameter-specific quality ratings and weights rather than individual concentration measurements. This distinction is important because the numerical influence of each parameter depends on its measured value, reference standard, and weighting coefficient.

3.3 Microbiological Quality of Spring Water

Microbiological assessment revealed differences in total coliform and *E. coli* concentrations among the six investigated spring-water sources (Table 2). Total coliforms were detected in all springs, ranging from 7 to 80 CFU/100 mL. The highest concentrations (80 CFU/100 mL) occurred at Ngesong, Banyuning, Gemulo, and Kasanan, while Torong Belok and Darmi recorded lower concentrations (7 CFU/100 mL). All measurements exceeded the adopted reference criterion of 0 CFU/100 mL, indicating potential microbiological vulnerability despite the generally low turbidity and favourable physicochemical characteristics. Total coliforms are widely distributed in natural environments, including soil, vegetation, and surface water, and their occurrence may reflect

environmental microbial inputs rather than exclusively faecal contamination. Possible contamination pathways include the transport of soil-associated microorganisms during rainfall, infiltration of surface runoff, accumulation of decomposing vegetation near spring outlets, and microbial growth within spring collection structures. However, the present study did not include sanitary inspections, rainfall-related sampling, or microbial source-tracking assessments to confirm these pathways. Therefore, the widespread occurrence of total coliforms should be interpreted as an indication of potential vulnerability rather than definitive evidence of direct surface-water intrusion. These findings highlight the need for improved spring protection, routine microbiological monitoring, sanitary inspections, and appropriate disinfection to ensure drinking-water safety.

The detection of *E. coli* at Ngesong (20 CFU/100 mL) and Darmi (1 CFU/100 mL) indicates faecal contamination and potential exposure to enteric pathogens, despite the generally favourable physicochemical characteristics of these springs. According to WHO (2022), *E. coli* should not be detectable in any 100 mL drinking-water sample. Possible sources of contamination include leakage from poorly constructed or unlined sanitation facilities, livestock manure, agricultural organic fertilizers, and surface runoff transporting faecal material into groundwater recharge areas or spring collection structures. Nevertheless, the presence of these potential contamination sources within a 50-m radius of Ngesong and Darmi was not verified because detailed sanitary inspections and surrounding land-use assessments were beyond the scope of this study. WHO (2024) recommends systematic sanitary inspections of spring-water sources to identify nearby sanitation facilities, livestock activities, and potential contamination pathways. Therefore, future investigations should incorporate sanitary surveys, evaluation of spring protection structures, and microbiological monitoring during different rainfall conditions. Appropriate treatment and disinfection are essential before the affected spring water is supplied for drinking purposes.

Despite these microbiological findings, all springs were classified as excellent based on their physicochemical WAWQI values (0.776–4.060). Similar discrepancies were reported by Zelalem et al. (2026), highlighting that favorable physicochemical quality does not guarantee microbiological safety. These results emphasize the importance of independent microbiological monitoring, source protection, and appropriate treatment before municipal distribution.

Table 2. Microbiological characteristics and compliance status of the six spring-water sources

Spring-water source	<i>E. coli</i> (CFU/100 mL)	Total coliform (CFU/100 mL)	<i>E. coli</i> criterion met	Total coliform criterion met
S1	20	80	No	No
S2	0	80	Yes	No
S3	0	80	Yes	No
S4	0	7	Yes	No
S5	1	7	No	No
S6	0	80	Yes	No

Note : S1=Ngesong, S2=Banyuning, S3= Gemulo, S4=Torong Belok, S5=Darmi, S6=Kasinan, RV= Reference value

3.4 Implications for Spring-Water Quality Monitoring and Management

The comparison between physicochemical WAWQI classifications and microbiological findings revealed contrasting water-quality conditions across the six spring sources (Figure 3). All springs were classified as excellent based on WAWQI values ranging from 0.776 to 4.060. However, total coliforms were detected in all sources (7–80 CFU/100 mL), while *E. coli* was detected at Ngesong (20 CFU/100 mL) and Darmi (1 CFU/100 mL). These findings demonstrate that favorable physicochemical quality does not guarantee microbiological safety, consistent with observations reported by Zelalem et al. (2026).



Figure 3. Comparison of (a) WAWQI values, and physicochemical classification, (b) microbiological contamination status of the investigated spring-water sources in Batu. All six springs fall in the excellent water-quality class. Microbiological contamination status in CFU/100 mL unit.

One of the most important findings of this study was the discrepancy between physicochemical water-quality classification and microbiological safety. Ngesong Spring exhibited the lowest WAWQI value (0.776), indicating the most favourable physicochemical characteristics among the six investigated springs. However, the same spring recorded the highest *E. coli* concentration (20 CFU/100 mL), exceeding the drinking-water requirement of zero *E. coli* per 100 mL. This contrast highlights a fundamental limitation of physicochemical-based water-quality indices: a favourable WAWQI score cannot establish microbiological safety. Consequently, exclusive reliance on chemical index scores may underestimate microbiological hazards and result in inappropriate drinking-water management decisions. The findings emphasize the necessity of integrating physicochemical assessment with independent microbial monitoring in municipal raw-water management. Although all investigated springs exhibited excellent physicochemical quality, appropriate treatment, disinfection verification, and continued surveillance remain essential. Water sources should not be considered suitable for direct consumption solely on the basis of favourable WAWQI classifications when microbiological contamination is detected.

In addition to routine physicochemical and microbiological monitoring, prompt on-site sanitary inspections are recommended to identify and mitigate potential contamination

pathways at all six springs. Priority measures should include inspecting concrete spring collection structures for cracks and leakage, improving surface drainage, maintaining protective covers, and installing perimeter fences to restrict livestock access and other potentially contaminating activities. An initial sanitary protection zone of at least 15 m around each spring should also be considered, within which agricultural activities, fertilizer and manure application, and new septic tanks or sanitation facilities are restricted. The final extent of these protection zones should be established according to local hydrogeological conditions and relevant regulations. Such preventive measures, combined with regular sanitary inspections and appropriate water treatment, would strengthen source protection and reduce potential microbiological contamination risks.

The detection of *E. coli* at Ngesong (20 CFU/100 mL) and Darmi (1 CFU/100 mL) highlights potential public health risks associated with the direct consumption of untreated spring water. According to WHO (2022), *E. coli* should not be detectable in any 100 mL drinking-water sample, as its presence indicates faecal contamination and the possible occurrence of enteric pathogens. Therefore, effective disinfection is essential before these water sources are supplied for drinking purposes. Chlorination or appropriately validated ultraviolet (UV) disinfection may be considered according to the characteristics of the water supply system (Chen et al., 2023). For chlorinated systems, maintaining and routinely monitoring adequate free residual chlorine throughout the distribution network is important to reduce the risk of microbial recontamination (WHO, 2022). Although UV treatment can effectively inactivate microorganisms, it does not provide residual disinfectant protection within pipelines, making distribution-system integrity and supplementary protective measures particularly important. Accordingly, Perumda Among Tirto should ensure effective disinfection, routine microbiological monitoring, and appropriate distribution-system management.

The contrasting physicochemical and microbiological findings highlight the need for an integrated water-quality assessment framework. Although WAWQI provides a useful quantitative evaluation of physicochemical conditions, it does not adequately represent microbiological contamination hazards. For example, Ngesong Spring exhibited the lowest WAWQI value (0.776), indicating favourable physicochemical water quality, but simultaneously recorded the highest *E. coli* concentration (20 CFU/100 mL). Future studies should therefore consider developing a two-tier classification framework combining physicochemical WAWQI scores with an independent Microbial Risk Matrix based on *E. coli* detection, total coliform concentrations, and sanitary inspection findings. Within this framework, microbiological non-compliance would trigger a water-safety warning regardless of the physicochemical classification, preventing favourable chemical scores from masking faecal contamination. Integration of both assessment components into a unified water-safety dashboard could support municipal utilities in identifying contamination hazards, prioritizing treatment interventions, and improving drinking-water management. Nevertheless, the proposed framework requires validation through repeated sampling, seasonal monitoring, and evaluation of its operational effectiveness.

4. CONCLUSION

This study evaluated the physicochemical and microbiological characteristics of six spring-water sources used for municipal drinking-water supply in Batu City, Indonesia. The Weighted Arithmetic Water Quality Index (WAWQI) indicated excellent physicochemical water quality across all investigated springs, with values ranging from 0.776 at Ngesong to 4.060 at Banyuning. Most physicochemical parameters complied with the selected reference criteria, although Banyuning exhibited a slightly acidic pH (6.46) and elevated color (15 TCU). Relatively higher nitrate concentrations (11 mg L⁻¹) were also recorded at Gemulo and Darmi, highlighting variations in water-quality characteristics among the sources.

Despite favorable WAWQI classifications, microbiological analysis revealed contamination across the investigated springs. Total coliforms were detected in all six sources (7–80 CFU/100 mL), while *Escherichia coli* was identified at Ngesong (20 CFU/100 mL) and Darmi (1 CFU/100 mL). Notably, Ngesong exhibited the lowest WAWQI value but the highest *E. coli* concentration, demonstrating that excellent physicochemical classifications do not necessarily indicate microbiological safety.

These findings emphasize the importance of integrating WAWQI-based physicochemical assessment with independent microbiological monitoring to support municipal raw-water management. Priority should be given to repeated microbiological examinations, sanitary inspections, and source protection, particularly at Ngesong and Darmi.

Since the assessment was conducted within a limited sampling period, further investigations covering wet and dry seasons are recommended to determine temporal variability and potential contamination pathways. Future investigations should adopt an integrated, multi-temporal water-quality monitoring strategy that combines seasonal assessments with automated, high-frequency measurements and rainfall-triggered sampling. Continuous monitoring of rainfall intensity, turbidity, pH, electrical conductivity, and water temperature, supported by periodic nitrate and microbiological analyses, would provide a more comprehensive understanding of water-quality dynamics in Batu City's volcanic spring systems. Additional sampling before, during, and after intense rainfall events is particularly recommended to investigate potential runoff-driven transport of faecal microorganisms and agricultural nutrients into spring recharge areas. Such monitoring would help identify short-term contamination events that may be overlooked by conventional seasonal sampling and support early-warning systems, targeted spring protection measures, and more effective drinking-water management.

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