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ORIGINAL RESEARCH ARTICLE

Aligning safe water access with SDG 6: A yearlong multisite assessment of drinking water quality in East Java, Indonesia

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Abstract: Drinking water quality in East Java is a significant concern for achieving Sustainable Development Goal (SDG) 6 on safe drinking water and adequate sanitation. This study analyzed and monitored drinking water quality over 12 months, with monthly sampling at six water source points in East Java, covering physical, chemical, and microbiological parameters. We used a case study method with Spearman's rank correlation analysis. Based on our analysis, the physical parameters were odorless, met regulatory standards, and were suitable for consumption. In addition, color values remained below 0.33 on the Pt-Co scale. Chemical parameters showed that the average pH ranged from 7.36 to 7.42, total dissolved solids levels between 131.83 and 135.42 mg/L, and Fe levels between 0.032 and 0.043 mg/L. Most locations showed Mn levels below the detection limit (<0.006 mg/L), with occasional detectable values up to 0.033 mg/L. Residual chlorine concentrations during the monitoring period ranged from 0.35 to 0.41 mg/L, and no indicator bacteria were detected. Microbiological indicators did not detect *Escherichia coli* or coliform bacteria, indicating that the drinking water met microbiological safety requirements. Our results underscore that drinking water quality at the six monitoring stations in East Java is satisfactory, though there are temporal differences in some locations. Emphasis should be placed on regular monitoring to ensure that water quality is maintained in reservoirs and remains suitable for consumers, thereby supporting progress toward SDG 6.

Keywords: Drinking water quality; Water bodies; Health; Sustainable Development Goals

1. Introduction

Freshwater has become one of the most critically scarce resources on Earth. The survival of plants, animals, and humans is highly influenced by water availability. Therefore, safeguarding the quality of water sources is crucial. Water plays a vital role in daily life, including drinking, domestic, and economic uses; therefore, maintaining its quality is essential because it directly affects human health.[1] Water pollution poses a danger to the long-term sustainability of water sources, with repercussions for ecological balance, public health, and economic activities.[2] Water quality plays a vital role in safeguarding public health and supporting environmental sustainability, as contaminated water can result in a variety of diseases and disrupt the stability of ecosystems.[3] Concerns about drinking water that fails to meet established health standards have become a major global public health issue and an important focus of research. This issue is critical because substandard water quality contributes to a wide range of diseases, particularly diarrhea.[4] An estimated 2 billion people worldwide consume water contaminated with fecal matter, and 5–10 million deaths occur each year from illnesses linked to unsafe or polluted water.[5] Numerous factors contribute to this contamination, including human activities and environmental conditions such as climate variability, topography, and flooding.[6]

Safe drinking water must comply with established standards, ensuring that it is free from pathogenic microorganisms, physical impurities, and chemical substances that may pose risks to human health.[7] One approach to assessing water safety involves evaluating consumer-oriented attributes, including taste, odor, and other esthetic characteristics such as overall appearance.[8] The discharge of waste from agriculture, slaughterhouses, and other industries can increase concentrations of heavy metals and pathogenic microorganisms in water bodies.[9]

Drinking water pollution by heavy metals and microorganisms has been linked to various diseases worldwide, underscoring the importance of quality evaluation of all drinking water sources.[10] Many customer complaints about drinking water are caused by variations in pH, mineral content, and organic substances.[11] According to the Household Drinking Water Quality Study,[12] only 11.8% of the population has access to potable drinking water. Indonesia's vast and diverse geography results in regional variation in the availability of drinking water sources.

Consumption of clean water is crucial for survival. Daily water requirements vary according to metabolic rate, levels of physical activity, age, health status, and environmental conditions.[13] Currently, more than 5% of the world population consumes 3 L of water per day, whereas most people consume at least 1 L. For those working in hot climates, water demand can reach up to 16 L/day.[14] According to Van Dyke *et al.*,[15] only 89% of the world population has access to safe and adequate drinking water sources. In some areas, for example, Sub-Saharan Africa, only 40–80% of community residents have access to drinking water. In addition, drinking water contaminated with *Escherichia coli* is consumed by approximately 2 billion people.[16]

Water demand in Indonesia is projected to increase by 31% from 2015 to 2045, hence requiring a more efficient water resource management strategy to avoid future crises.[17] Therefore, efforts are needed to conserve water resources, adopt environmentally friendly technologies, and implement sustainable policies to ensure adequate water availability for future generations. In addition, active community participation in maintaining the cleanliness of water sources and reducing water waste is also a key factor in maintaining the balance of the water ecosystem.

A growing body of literature has examined drinking water quality in Indonesia over the past 15 years. To provide an overview of how research in this field has evolved, studies indexed in the Scopus database were compiled and analyzed to examine publication trends. The resulting trend, covering the period from 2010 to 2025, is presented in Figure 1. As shown in the figure, the number of publications peaked in 2023 at 23, followed by a sharp decline to 6 in 2025.

Researchers are addressing the increasing issue of water pollution through enhanced monitoring and management of water quality.[18] Public awareness of the importance of protecting drinking water is growing, along with the worsening pollution conditions in drinking water resources.[19,20] However, conventional systems for detecting water quality have various disadvantages, such as high cost, large size, inability to transmit parameters remotely, and the capacity to measure only one parameter at a time.[21]

Pure water and adequate sanitation are basic human needs that not only directly affect health but also social, economic, and environmental welfare.[22] The provision and management of clean water are essential to achieving Sustainable Development Goal (SDG) 6,

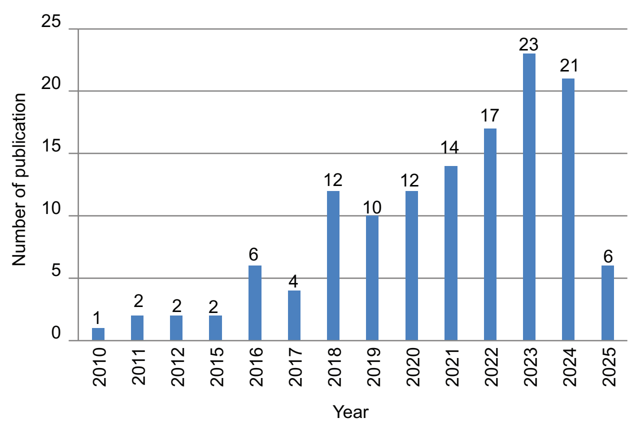

Figure 1. Publication trends according to the Scopus database from 2010 to 2025

which relates to the availability and sustainability of clean water. Routine and systematic monitoring allows potential contamination to be identified at an early stage, enabling timely preventive action. Such measures are essential not only for maintaining ecological balance in water systems but also for reducing the likelihood of future water shortages or crises.[23] Water quality evaluation commonly relies on measurements of key chemical and physical parameters, as these indicators alone are generally sufficient to determine whether water poses risks when consumed or used by humans.[24]

Although research on drinking water has increased over the past decade, publication trends still reveal a clear methodological gap. Many existing studies are based on short-term observations or rely on a single sampling point, whereas long-term monitoring across multiple locations is rarely undertaken. This issue is particularly critical in regions such as East Java, where growing environmental pressures and rapid urban expansion demand assessment approaches that are not only continuous but also spatially comprehensive.

This study was designed to address methodological shortcomings identified in drinking water research in Indonesia over the past 10 years. To overcome these gaps, we adopted a longitudinal case study approach. This method enabled examination of both temporal changes and spatial differences in greater detail—insights that cannot be captured through 1-time surveys or single-point sampling. Consequently, monitoring was conducted regularly over 12 months and included a comprehensive assessment of three parameter groups: Physical (odor and color), chemical (pH, total dissolved solids [TDS], Fe, Mn, residual chlorine, and Al), and microbiological (*E. coli* and total coliform).

Through the monthly observation of these parameters, the study provides a realistic representation of the conditions people encounter in practice. The spatial range, together with continuous temporal monitoring, provides the latest data for local water management planning and contributes to achieving SDG 6, particularly targets related to safe drinking water, water quality improvement, and water resources' long-term sustainability.

2. Materials and methods

2.1. Materials

The study used standard sampling equipment and laboratory instruments for physical, chemical, and microbiological analyses (Table 1). The water samples were filtered through 47 mm membrane filters in accordance with ISO 9308–1:2010/Amd 1:2016, and then cultured on chromogenic coliform agar (CCA) media in Petri dishes. The dishes were incubated at 36 ± 2°C. Physical analyses were performed using a spectrophotometer (DR3900, LPV440.99.00002, HACH, United States of America [USA]) to measure water color and a turbidimeter (HI 98703, Hanna, USA) based on nephelometry, with a tungsten lamp and a photoelectric detector, using formazin as the calibration standard. Chemical analyses were conducted using a pH

Table 1. Methodology summary

Aspects	Description
Research design	Case study with longitudinal time series analysis
Study period	12 months (January 5–December 3, 2024)
Sampling sites	6 strategic reservoir monitoring points (Outlet Umbulan, RM Bangil, RM Winongan, RM Sidoarjo, RM Putat Gede, RM Giri)
Sampling frequency	Monthly (n=12 observations per site)
Parameters monitored	11 total: 2 physical (odor, color), 7 chemical (pH, TDS, Fe, Mn, Al, residual Cl_2), 2 microbiological (*E. coli,* total coliform)
Analytical methods	• Spectrophotometry (color) • Nephelometry (turbidity) • Potentiometry (pH) • Gravimetric (TDS) • ICP-OES (metals) • DPD method (residual chlorine) • Membrane filtration (microbiological)
Statistical analysis	• Analysis for temporal dynamics • Spearman's rank correlation (ρ) for parameter relationships • Significance testing at $\alpha = 0.05$ • Software: R version 4.3.1 (Hmisc package)
Quality standards	Ministry of Health Regulation No. 2/2023 on drinking water quality requirements
Data interpretation	• Compliance assessment vs. regulatory standards • Identification of temporal trends and seasonal patterns • Correlation analysis with chemical mechanism interpretation • SDG 6 alignment assessment

Abbreviations: DPD: N, N-diethyl-*p*-phenylenediamine; ICP-OES: Inductively coupled plasma-optical emission spectrometry; SDG: Sustainable development goal; TDS: Total dissolved solids.

meter with a glass electrode, an oven at 103–105°C, a furnace at 550°C for TDS, and an analytical balance. The N,N-diethyl-*p*-phenylenediamine (DPD) method was used to determine residual chlorine with DPD reagent and potassium iodide, and the results were measured using a spectrophotometer (UV-1800, Shimadzu, Japan). On the other hand, heavy metals (Fe, Mn, Cd, Pb, Hg, and Cu) were measured by inductively coupled plasma-optical emission spectrometry (ICP-OES) (ICP-OES; ICPE-9000, Shimadzu, Japan) using argon gas as the excitation source. Meanwhile, for microbiological analysis, a 100 mL filtration unit was used along with membrane filters. The membranes were then incubated in CCA medium to detect coliforms and *E. coli*.

2.2. Methodology

This research used a case study with time-series analysis and Spearman's rank correlation (SRC) coefficient analysis to examine drinking water quality in depth across six water distribution systems in East Java province (Figure 2). A case study is a research strategy used to understand the dynamics in a particular setting. This approach involves an in-depth exploration of a real phenomenon, context, or event using various relevant sources of information.[25] In this study, the case study approach enabled a more detailed exploration of water quality at each water source location, allowing a contextual understanding of the characteristics, conditions, and interactions among various physical, chemical, and microbiological parameters over a specific period. The study ran from January to December 2024, with monthly sampling intervals at six sites. Sampling was conducted at monthly intervals rather than continuously; therefore, the study captured trends at the monthly timescale rather than short-term fluctuations. The six monitoring sites are located at the essential nodes of the East Java raw water distribution network, around which the network was traced. Umbulan Outlet (7.71°S, 112.75°E) serves as the primary source point, from which water is drawn directly from the Umbulan spring system. The other five places were reservoir meter (RM) points that are spread out along the major transmission corridor: RM Bangil (Pasuruan city, 7.60°S, 112.82°E), RM Winongan (Pasuruan regency, 7.69°S, 112.80°E), RM Sidoarjo (Sidoarjo regency, 7.45°S, 112.71°E), RM Putat Gede (Surabaya city, 7.31°S, 112.72°E), and RM

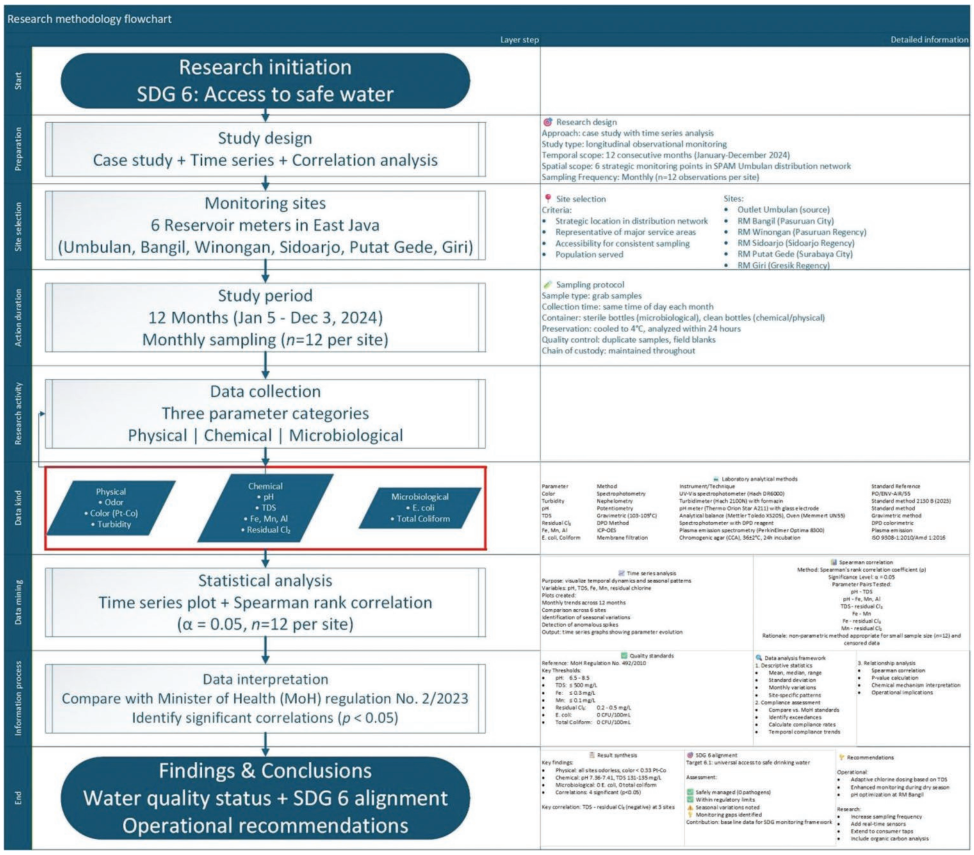

Figure 2. Research methodology flowchart

Abbreviation: SDG: Sustainable Development Goal.

Giri (Gresik regency, 7.17°S, 112.60°E). An RM is a metering station installed by the water supply authority at the source point to measure incoming water flow. These sites were selected due to their strategic roles in channeling raw water across multiple administrative regions, the size and diversity of the populations they serve, and their suitability for reliable monthly sampling. Collectively, the six points provide a representative spatial profile of water quality dynamics along the regional supply pathway.

This study employed multiple laboratory test methods to examine water samples suitable for human consumption. Three parameter groups—physical (color and turbidity), chemical (pH, TDS, residual chlorine, Fe, Mn, Pb, Hg, Cr, and Cd), and microbiological (*E. coli* and total coliform)—were used to characterize the monitored water.

2.3. The influence of environmental factors, infrastructure, and community activities on water quality

Water quality changes at the six monitoring points can be attributed to environmental factors, the condition of the infrastructure, and the activities of the community around the water sources. In places such as Sidoarjo and Gresik, where there is a high density of population along with a lot of industrial and agricultural activities, a trend of slightly increased levels of TDS and metals, including Fe and Mn, was observed. Several factors, including domestic wastewater runoff and the use of fertilizers and pesticides, drive this phenomenon. In contrast, the Umbulan and Winongan areas—where relatively clean mountain spring water is distributed through a gravity-fed system—exhibited more stable physical and microbiological quality.

The test results indicated that *E. coli* counts were zero at all sampling points, suggesting the absence of fecal contamination. Consequently, the risk of water-borne diseases such as diarrhea and dysentery is considerably reduced. On the other hand, elevated Fe levels were recorded during certain months. However, these levels remained within acceptable limits; they may cause organoleptic issues such as a metallic taste and a yellowish discoloration, and can also contribute to the corrosion of distribution pipelines. These findings, therefore, highlight the importance of regular infrastructure maintenance and routine inspections of both drinking water sources and their distribution systems.

2.4. Time-series analysis

To analyze the dynamics of water quality over time, a time-series analysis was used. This analysis aims to visualize changes in the trends of water quality, such as TDS, pH, Fe, Mn, and residual chlorine, over the observation period. This time-series data allows the identification of seasonal patterns and monthly fluctuations, as well as the early detection of environmental anomalies that have the potential to affect water quality. In addition, the time-series data were used to strengthen the interpretation of the relationship between chemical and physical measurements and to provide a basis for evaluating the sustainability of water quality against drinking water quality standards set by national regulations.

2.5. SRC analysis per city spot

SRC analysis is a non-parametric statistic for assessing the relationship between two variables. SRC measures the strength and direction of the monotonic relationship between two continuous variables.

3. Results and discussion

3.1. Water quality monitoring

At each monthly sampling campaign, water quality at the RM outlet was monitored over a 24-h period from January 5 to December 3, 2024. The assessment covered three categories of parameters before distribution to consumers: physical parameters (odor and color), chemical parameters (pH, TDS, Fe, Mn, Al, and residual chlorine), and microbiological parameters (*E. coli* and total coliform). The spatial coverage of the water distribution system and sampling locations across East Java are illustrated in Figure 3.

3.1.1. Physical parameters

Odor is one of the important parameters for assessing water quality. Water that has an unpleasant odor may indicate biological, chemical, or waste contamination that affects water quality. Based on the observations over 12 months (Table 2), water at the six locations—Umbulan, Winongan, Bangil, Sidoarjo, Putat Gede, and Giri—did not have an odor. Drinking water is considered acceptable if it meets the physical requirements of being non-turbid, colorless, and odorless.[26] Based on the Ministry of Health (MoH) regulation No. 2 of 2023, drinking water must meet the quality requirements set by the government, such as the physical requirements of being colorless, odorless, and tasteless.[12] Hence, under MoH regulation No. 2 of 2023, the odor parameters of the six locations meet drinking water standards, and the water is drinkable.

The presence of organic materials (such as plankton and humus) or inorganic materials (such as iron and manganese ions) can cause discoloration.[27] In other

Table 2. Spearman's rank correlation analysis between parameters at the monitored sites

Parameter pair	Reservoir meter (RM) points											
	Outlet Umbulan		RM Winongan		RM Bangil		RM Sidoarjo		RM Putat Gede		RM Giri	
	Spearman rho	*p*-value	Spearman rho	*p*-value	Spearman rho	*p*-value	Spearman rho	*p*-value	Spearman rho	*p*-value	Spearman rho	*p*-value
pH-total dissolved solids	0.2867	0.3663	0.4842	0.1107	0.6544	0.0210	0.3445	0.2729	0.3462	0.2703	0.4308	0.1621
pH-Fe	−0.3930	0.2063	0.4812	0.1132	−0.1508	0.6400	−0.0875	0.7869	0.6253	0.0297	0.2369	0.4584
pH-Mn	-	-	−0.1745	0.5865	-	-	−0.3062	0.3330	-	-	-	-
pH-Residual Cl_2	−0.1119	0.7292	−0.1778	0.5803	−0.6151	0.0333	0.1673	0.6034	−0.0422	0.8964	−0.1655	0.6072
Total dissolved solids–Fe	−0.4804	0.1139	−0.1312	0.6843	0.1104	0.7327	0.2191	0.4938	0.2625	0.4098	0.2527	0.4282
Total dissolved solids–Mn	-	-	−0.4812	0.1132	-	-	0.4821	0.1125	-	-	-	-
Total dissolved solids–Residual Cl_2	−0.1958	0.5419	−0.5775	0.0493	−0.4552	0.1370	−0.0582	0.8574	−0.5616	0.0574	−0.5905	0.0432
Fe–Mn	-	-	−0.0909	0.7787	-	-	−0.0909	0.7787	-	-	-	-
Fe–Residual Cl_2	0.4804	0.1139	0.4390	0.1533	0.4370	0.1555	0.1317	0.6833	−0.0415	0.8982	0.0270	0.9336
Mn–Residual Cl_2	-	-	0.2195	0.4930	-	-	0	1	-	-	-	-

Note: Several correlation values are unavailable because the corresponding parameters had constant values (no variation) or insufficient data at specific sampling locations, making the Spearman correlation impossible to compute.

words, higher concentrations of dissolved substances are often associated with more intense visible color, which can significantly affect water quality.[28] The color of the water can be observed directly or measured using a platinum-cobalt scale and expressed in Pt-Co units by comparing the water sample's color to a standard color.[12] Based on Table 3, the analysis of color parameters at six observation locations indicated an overall value of <0.33 Pt-Co units. The maximum color parameter allowed for drinking water is 15 Pt-Co units.[12] Therefore, it can be concluded that the water at the six sites meets the color quality standard.

3.1.2. Chemical parameters

As an important parameter in assessing water quality, pH can affect biological and chemical processes. Drinking water should have a neutral pH because the pH value is related to the effectiveness of chlorination.[29] pH can control the balance of carbon dioxide, carbonate, and bicarbonate.[30] According to research by Adams *et al*.,[31] the standard clean water pH is 6.5–9.0, whereas drinking water is 6.5–8.5. Water with a pH below 6.5 can cause corrosion in pipes, potentially releasing heavy metals such as lead and copper into drinking water. Therefore, long-term consumption of low-pH drinking water can increase the risk of heavy metal poisoning.[30] According to the World Health Organization (WHO),[7] long-term consumption of drinking water with a high pH can disrupt the acid balance in the stomach and digestive system, causing digestive disorders in some people.

The research findings show that pH levels alternated between decreases and increases each month. Environmental factors and human activities can influence this. High pH levels were recorded in June, whereas low pH levels occurred in March. The six sites had average pH levels between 7 and 8. Based on these results, it can be concluded that the water pH at the six observation locations is within the drinking water standard range of 6.5–8.5, as specified in MOH Regulation No. 2 of 2023.

TDS represents the combined concentration of dissolved organic and inorganic substances in water, including organic and inorganic matter. Clearwater without visible sediment and with TDS below 500 mg/L is generally considered suitable for consumption.[32] High TDS levels may indicate the presence of harmful contaminants.[33] As shown in Table 3, TDS results from the six locations showed that most of the water tested had TDS levels below 200 mg/L. The highest TDS levels were in Putat Gede in January (162 mg/L; Table S14), whereas the lowest TDS levels were in Winongan and

Table 3. The six sites of yearlong monitoring of drinking water quality

Parameter	Outlet Umbulan		RM Winongan		RM Bangil		RM Sidoarjo		RM Putat Gede		RM Giri	
	Rate1	Dev1	Rate2	Dev2	Rate3	Dev3	Rate4	Dev4	Rate5	Dev5	Rate6	Dev6
pH	7.415	0.129	7.388	0.139	7.412	0.112	7.396	0.108	7.373	0.113	7.364	0.116
Total dissolved solids (mg/L)	132.583	10.583	131.833	12.028	132.667	11.056	133.750	12.375	134.667	12.611	135.417	11.417
Iron (Fe) (mg/L)	0.043	0.020	0.032	0.000	0.033	0.001	0.039	0.013	0.037	0.009	0.033	0.002
Residual chlorine (Cl_2) (mg/L)	0.393	0.053	0.414	0.092	0.364	0.058	0.390	0.053	0.369	0.061	0.349	0.069
Manganese (Mn) (mg/L)	<0.006		0.008	0.004	<0.006		0.006	0.001	<0.006		<0.006	
Aluminum (Al) (mg/L)	<0.033											
Escherichia coli (CFU/100 mL)	0.00											
Total coliform (CFU/100 mL)	0.00											
Color (Pt-Co units)	<0.330											
Odor	Odorless											

Abbreviation: RM: Reservoir meter.

Giri in March (107 mg/L; Table S16). Based on these results, it can be stated that the water tested meets the quality standards of the MoH Regulation No. 2 of 2023 (maximum permitted TDS: 500 mg/L).[12] According to Pushpalatha *et al*.,[34] high TDS levels in water can cause health problems such as gastrointestinal disorders and toxic effects of dissolved heavy metals.

Iron metal is naturally found in the form of compounds in rocks, soil, and water. It can also originate from human activities, such as pollution from fuel, industrial waste, domestic waste, livestock, and agricultural and plantation activities.[35] Based on Table 3, Fe levels at the six locations were mostly below the detection limit of the device (<0.032 mg/L). However, some exceptions were found, such as in Umbulan in March (0.16 mg/L; Table S16), Winongan in June (0.034 mg/L; Table S19), Bangil in July (0.033 mg/L; Table S20), Putat Gede in August (0.091 mg/L), and Sidoarjo (0.119 mg/L; Table S21) and Giri (0.045 mg/L; Table S22) in September. Although there was a spike in Fe levels at specific times and locations, all detected values were below the threshold set by MoH Regulation No. 2 of 2023 (<0.3 mg/L),[36] as well as the WHO standards for drinking water quality. Thus, the Fe levels were considered safe. However, regular monitoring is still recommended, especially at points where levels were elevated. It should be noted that Fe oxidation can cause changes in color and taste in water, as well as increase the number of dissolved particles.[18,19,35] In addition, Fe accumulation can cause corrosion in water piping systems, potentially damaging infrastructure and reducing water quality.[19,37] Long-term exposure to excessive Fe has been associated with an increased risk of neurodegenerative diseases such as Parkinson's disease.[38]

From Table 3, most locations showed Mn levels below the detection limit (<0.006 mg/L), except in Sidoarjo in January (0.012 mg/L; Table S14) and Winongan in March (0.033 mg/L; Table S16). In general, the Mn levels detected were within safe limits. Mn in water may originate from natural sources and human activities. Naturally, Mn is present in rocks and soil and can dissolve into water through mineral dissolution. Meanwhile, human activities, such as industrial waste disposal and fertilizer use, can also increase manganese levels in water. In MoH Regulation No. 2 of 2023, the quality standard for class I water—water that can be used as raw water for drinking water—is that the Fe concentration is below 0.2 mg/L and Mn below 0.05 mg/L. Exposure to excessive Fe and Mn may influence water esthetic value (color, sediment, and taste) and can indirectly affect human health.[39,40] Mn is an essential element for human health. Adequate levels of Mn are needed to support brain function, primarily due to its role in various metalloproteins, such as superoxide dismutase, mitochondrial enzymes, and glutamine synthetase. However, excessive levels of Mn may cause intellectual impairment, visual motor skills, attention, and memory loss, hyperactivity, aggressive behavior, and motor dysfunction.[41-43] In addition, Mn neurotoxicity syndrome results from long-term exposure to Mn in the nervous system. The syndrome is characterized by slow speech, anorexia, weakness, flat facial expression, tremors, muscle pain, rigidity, apathy, and decreased mental status.[18]

Aluminum in water generally originates from the weathering of aluminosilicate minerals or industrial activities, such as metal and chemical production. However, in natural conditions, especially in waters with neutral-to-alkaline pH, Al levels tend to be low. A study by Wanta[44] showed that Al is highly soluble in acidic environments and can precipitate at higher pH. From Table 3, the Al concentration remained consistently below the detection limit (<0.033 mg/L) throughout the year. This level is considered very low and safe by the WHO international standard, which sets a threshold of 0.2 mg/L.[45] Findings from various epidemiological studies showed that long-term consumption of Al through drinking water has the potential to cause severe health impacts[14,46] and is positively correlated with the risk of AD.[15,45,47]

Referencing Table 3, most residual chlorine levels fell within the recommended range of 0.2–0.5 mg/L, except Winongan during May–July (0.511–0.52 mg/L) and Umbulan (0.52 mg/L), and Putat Gede (0.50 mg/L) in March. According to MoH Regulation No. 2 of 2023, these concentrations remain acceptable, as they are close to the regulatory threshold. Residual chlorine at this level indicates that the disinfection process is functioning effectively in suppressing pathogenic microorganisms while keeping the water safe for consumption.[48] Residual chlorine in drinking water is important for disinfection, but exceeding 0.5 mg/L can harm health. Excessive chlorine exposure can irritate the skin, eyes, and respiratory tract, as well as result in disorders of the digestive system.[49] In addition, chlorine can react with organic matter in water and form hazardous compounds, such as trihalomethanes (THMs), which are carcinogenic.[50] Long-term exposure to THMs has been associated with an increased risk of bladder cancer and impaired liver function.

3.1.3. Microbiological parameters

Analysis of *E. coli* content showed that throughout the year, no *E. coli* contamination was detected

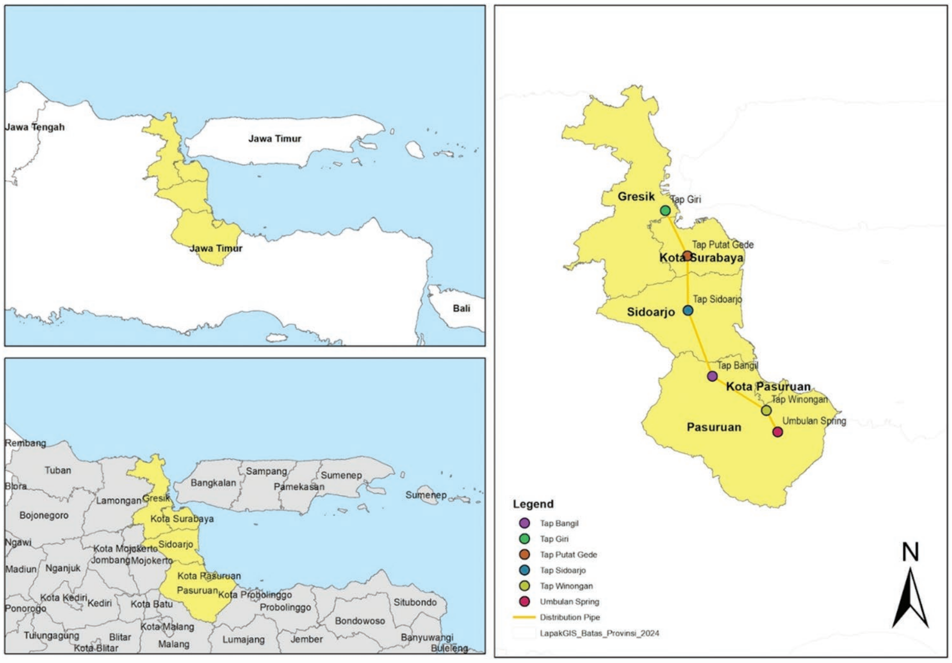

Figure 3. Water distribution system

in any of these locations (Table 3). These results indicate water quality that meets environmental health standards. The absence of *E. coli* suggests that water sources in this area are in hygienic conditions, which are important to prevent water-based diseases such as diarrhea and gastrointestinal infections.[51] Success in maintaining water quality indicates the effectiveness of the sanitation management system and consistent periodic monitoring.[52] Consuming water contaminated with *E. coli* can cause diarrhea, nausea, vomiting, and abdominal pain.[53] These symptoms are the body's response to bacterial infection in the gastrointestinal tract. *E. coli* is the leading indicator of fecal contamination in water. Its presence indicates the potential for other water-borne pathogens, such as cholera and typhus.[54]

Meanwhile, based on Table 3, total coliform testing at the six locations showed similar results: no coliform was detected throughout the year. Total coliform is used as an early indicator of potential biological pollution in water sources.[55] The absence of coliforms in water samples indicates that the water tested is safe for consumption and complies with the drinking water quality standards set by MoH Regulation No. 2 of 2023, which stipulates that qualified drinking water has no detected coliforms and *E. coli* per 100 mL of sample.[12] Consuming water contaminated with coliforms can cause diarrhea, intestinal infections, and fever. In severe cases, it can develop into more serious diseases

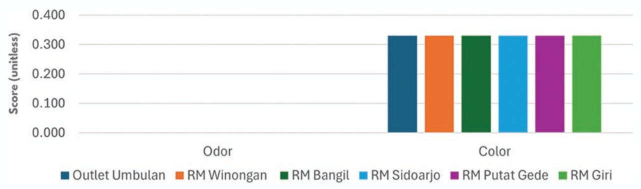

Figure 4. Physical data

such as hemolytic uremic syndrome.[56] Toddlers, the elderly, and individuals with weak immune systems are particularly susceptible to these infections, potentially leading to severe complications and even death.[57] Consistent monitoring and negative results for these two microbiological parameters demonstrate a strong commitment to achieving SDG 6, especially in the area of universal access to safe and affordable drinking water, as well as encouraging sustainable improvements in the quality of public health.

3.2. Time-series analysis

The trend at each sampling point was analyzed based on data collected monthly over 12 months. Figure 4 illustrates the pH levels across six sampling sites, showing that pH at all locations tends to be stable, ranging from 7 to 8. The pH during certain months, such as June, August, and September, approached 8, whereas in March, May, and December, it decreased to around 7 (Tables S14-S25). Weather factors, rainfall, human activities around the water source, or changes in water ion content, such as carbonate, bicarbonate, and heavy metals, may cause this.[58]

The TDS measurements at the six locations from January to December showed significant changes throughout the year (Tables S14-S25). In March, all water sources experienced a drastic decrease in TDS values to around 110 mg/L. This decrease may reflect high rainfall at the beginning of the year, which diluted the concentration of dissolved substances in the water.[59] Furthermore, the TDS values gradually increased until, in August, they reached 155 mg/L. This increase may be related to the dry season, which causes higher water evaporation, thereby increasing the concentration of dissolved substances.[30]

The levels of Fe at the six sampling spots showed unstable trends from January to December (Tables S14-S25). Several significant spikes were observed in Umbulan in April and October, and in Putat Gede in August. The majority of sources showed low or undetectable Fe levels in most months, except at certain times, suggesting the possibility of temporary contamination from anthropogenic activities or changes in local environmental conditions.[60] Although most data showed relatively safe Fe levels, the spikes require follow-up to ensure consistent water safety and quality.

According to Figure 5, Mn levels from the six water sources were generally extremely low and stable throughout the year. Slight increases were observed in Umbulan in January and in Winongan in March (Tables S14 and S16). Overall, Mn levels were far

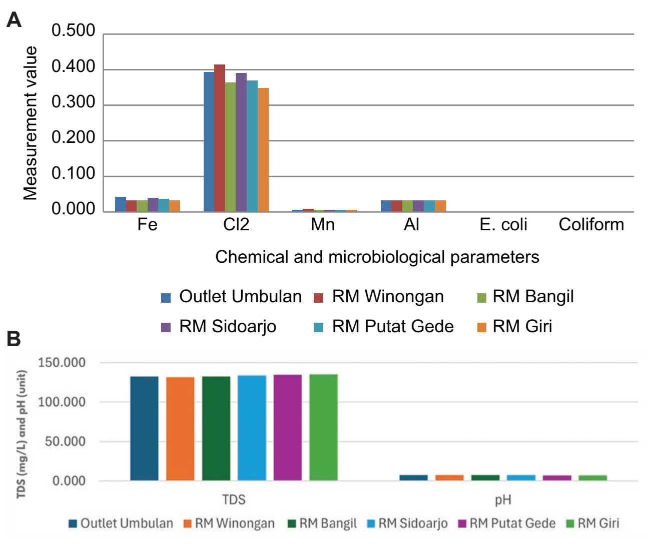

Figure 5. Chemical and microbiological data. (A) Levels of Fe, Cl_2, Mn, Al, *Escherichia coli*, and coliform. (B) pH and total dissolved solids of water samples.

below the maximum threshold set by MoH Regulation No. 2 of 2023, which aims to prevent color and taste disturbances in water and accumulation of heavy metals in the body. According to a study,[61] the presence of manganese in drinking water in high concentrations can pose health risks, especially for children, such as neurological dysfunction. Therefore, although there was a slight increase, the Mn levels indicate that the water quality from the six sources is still within safe limits for consumption and does not show any significant heavy metal contamination.

Residual chlorine levels across the six water sources from January to December ranged from 0.2 to 0.6 mg/L, indicating that water quality remains within safe limits for consumption (Tables S14-S25). According to the WHO, residual chlorine levels in drinking water must remain within 0.2–1.0 mg/L. Extremely low residual chlorine levels cannot eliminate harmful microorganisms. Conversely, if the levels are overly high, the water can smell bad and pose a health risk.[62] Although there were minor monthly fluctuations, no significant changes or extreme spikes were observed. The Winongan source tended to have slightly higher chlorine levels, whereas Putat Gede tended to be lower than the other sources. This shows that the management of residual chlorine in each source is relatively stable and consistent throughout the year.

The concentration of Al was consistently below 0.033 mg/L, indicating no significant fluctuations in Al levels at the sampling location (Figure 5). This condition suggests that anthropogenic activities with the potential to pollute water, such as industrial waste and the use of Al-based chemicals, are relatively low at this location. A study has shown that the stability of heavy metal levels in water can be affected by minimal sources of pollution and the effectiveness of domestic and industrial waste management in the surrounding area.[63]

Meanwhile, the concentrations of Pb in water were also low and stable, well below 0.003 mg/L (Figure 5). The absence of significant changes in Pb levels indicates that the sources of Pb pollution are limited or have been successfully controlled. This is important because Pb is a highly toxic and bioaccumulative heavy metal. As shown in a previous study,[64] Pb levels in the Hertasning Canal in Makassar city ranged from 0.134 to 0.47 mg/L, far exceeding the government-set threshold (0.008 mg/L based on PP No. 22 of 2021). Thus, the low Pb levels at our research locations are an indication of good and safe aquatic environmental conditions with respect to heavy metal contamination. In addition, according to research by Nuri *et al*.,[65] the accumulation of Pb in water can have negative impacts on aquatic organisms and humans if consumed continuously, even at low concentrations.

3.3. SRC analysis

The SRC analysis was conducted to assess the relationship between chemical and physical parameters at each sampling location. The parameters analyzed included pH, TDS, Fe, Mn, Al, and residual chlorine. The correlations found were explained in terms of the SRC and its interpretation, and are accompanied by relevant chemical formulas. Table 2 shows the SRC analysis between the parameters at the monitored sites.

The results of the SRC analysis are presented in Table 2. Table 4 presents significant correlations, with $p<0.05$, indicating relationships that are not due to random variation with 95% confidence. Across the six monitoring sites, six statistically significant correlations were identified. The most consistent pattern observed across multiple sites was the negative correlation between TDS and residual chlorine, which achieved statistical significance at two sites: RM Winongan ($\rho=-0.578$, $p=0.049$) and RM Giri ($\rho=-0.591$, $p=0.043$), and one site approached significance: RM Putat Gede ($\rho=-0.562$, $p=0.057$). This pattern indicates that higher concentrations of dissolved solids in water tend to be associated with lower residual chlorine following the disinfection process.

At the RM Bangil site, two significant correlations were observed. The first is a moderate positive correlation between pH and TDS ($\rho=0.654$, $p=0.021$), suggesting that water with higher dissolved solids tends to have higher pH values. This relationship is consistent with the buffering effect of alkaline components—particularly bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions—which contribute to TDS and pH stabilization. In water systems governed by carbonate buffering, these ions help maintain pH by neutralizing added acids or bases, as illustrated in the following reactions:

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2$$

Water derived from limestone or other carbonate-rich formations generally shows elevated TDS—primarily from calcium and magnesium carbonates—along with slightly higher pH values, typically 7.5–8.5. These conditions align with the hydrogeological setting of the Bangil source area. The positive correlation identified in this study indicates that higher mineral concentrations (TDS = 115–158 mg/L) were consistently associated with neutral-to-mild alkaline pH values (7.31–7.44).[66] In natural water systems, pH and TDS do not have a strong linear relationship, as TDS is more influenced by dissolved ions from pollution sources or local geological conditions, whereas pH is more influenced by the acid–base balance of water.

Second, a moderate negative correlation between pH and residual chlorine ($\rho=-0.615$, $p=0.033$) was observed at RM Bangil. This inverse relationship indicates that higher pH values correspond with lower residual chlorine concentrations. The chemical basis for this relationship lies in the pH-dependent speciation of chlorine in water. At lower pH (<7.5), chlorine exists predominantly as hypochlorous acid (HOCl), which is a more effective disinfectant but also more rapidly consumed through oxidation reactions. At higher pH (>7.5), chlorine shifts toward the hypochlorite ion form (OCl^-), which is more stable and persists longer as residual chlorine[67]:

$$HOCl \rightleftharpoons H^+ + OCl^- \ (pKa \approx 7.5)$$

However, the observed negative correlation suggests that at RM Bangil, higher pH is associated with lower rather than higher residual chlorine. This counterintuitive finding may indicate that: (i) chlorine dosing is adjusted based on pH, with lower doses applied to higher-pH water that requires less disinfection due to reduced microbial activity, (ii) higher-pH waters at this site contain more organic or inorganic constituents that exert chlorine demand, and (iii) operational factors such as

Table 4. Spearman's rank correlation analysis

Number	Site	Parameter pair	Spearman rho	*p*-value	Strength and direction
1	RM Bangil	pH-Total dissolved solids	0.6544	0.0210	Moderate positive
2	RM Bangil	pH-Residual Cl_2	−0.6151	0.0333	Moderate negative
3	RM Putat Gede	pH-Fe	0.6253	0.0297	Moderate positive
4	RM Putat Gede	Total dissolved solids-Residual Cl_2	−0.5616	0.0574	Moderate negative
5	RM Winongan	Total dissolved solids-Residual Cl_2	−0.5775	0.0493	Moderate negative
6	RM Giri	Total dissolved solids-Residual Cl_2	−0.5905	0.0432	Moderate negative

Abbreviation: RM: Reservoir meter.

contact time vary with source water chemistry. Further investigation of treatment protocols and source water characteristics would help elucidate the mechanism underlying this relationship.

The most robust finding across sites was the significant negative correlation between TDS and residual chlorine at RM Winongan and RM Giri. This relationship indicates that waters with higher dissolved solids content exhibit lower residual chlorine concentrations after treatment. Several mechanisms may contribute to this pattern:

(i) Chlorine demand from dissolved constituents: Elevated TDS often reflects increased concentrations of reduced species such as Fe^{2+}, Mn^{2+}, and organic compounds that react with and consume free chlorine. The oxidation of ferrous iron by chlorine, for example, proceeds according to:

$$2Fe^{2+} + Cl_2 \rightarrow 2Fe^{3+} + 2Cl^-$$

Similarly, dissolved Mn and natural organic matter (humic substances) exert chlorine demand through oxidation reactions. Water with higher TDS, particularly from groundwater sources with elevated metal content, would require greater chlorine doses to achieve the same residual concentration. Both parameters are common metals originating from the same geological source, especially in areas with sediments rich in metal minerals.[68]

(ii) Ionic strength effects: Higher TDS indicates elevated ionic strength, which can affect chlorine chemistry by influencing activity coefficients and reaction kinetics. In high-ionic-strength solutions, the formation of chloramines through reactions with ammonia or organic nitrogen may be enhanced, reducing free chlorine residuals.

(iii) pH co-variation: Even though the correlation analysis looked directly at the TDS-chlorine relationship, TDS and pH often shift together, as seen at RM Bangil. When TDS rises due to carbonate minerals, the pH usually increases as well. This change in pH then influences chlorine speciation and the persistence of residual chlorine in the water.

The consistent negative correlation between TDS and chlorine at RM Winongan and RM Giri, and the near-significant correlation at RM Putat Gede (ρ=−0.562, p=0.057), indicates that this pattern is not a one-off anomaly. It appears to be a recurring behavior across the whole distribution network. This has clear operational consequences: when TDS fluctuates, chlorine dosing must adapt to keep the disinfectant effective throughout the system. This need becomes even more critical during the dry season, when TDS levels usually climb.

At Outlet Umbulan, RM Sidoarjo, and partly at RM Putat Gede, none of the parameter pairs showed significant correlations. At Outlet Umbulan, pH and TDS showed a moderate trend (ρ=0.287), but the link was not sufficiently strong to be meaningful (p=0.362). This likely reflects the stable chemical characteristics of the source water at that major outlet. Meanwhile, at RM Sidoarjo, all correlation tests produced p-values far above 0.05. This suggests that the parameters may change independently, or that the water chemistry there remains steady throughout the year, making meaningful relationships harder to detect. It is also possible that the key processes affecting water quality were not fully captured by the variables included in this study.

The absence of significant correlations at these sites should not be interpreted as indicating "no relationships exist," but rather that monthly sampling with n=12 observations lacked sufficient statistical power to detect weak-to-moderate associations. Short-term dynamics occurring on hourly or daily timescales, which are likely crucial at these locations, would not be captured by this sampling protocol.

3.4. Implications of correlation analysis for water quality management

3.4.1. Chemical process interactions and operational implications

The Spearman's correlation analysis revealed systematic relationships among water quality parameters, providing insights into chemical processes within the East Java drinking water distribution network. The most consistent finding—the negative correlation between TDS and residual chlorine at three monitoring sites (RM Winongan, RM Giri, and trending at RM Putat Gede)—has direct operational significance for water utilities.

Waters with elevated TDS require higher chlorine doses to maintain adequate disinfectant residuals throughout the distribution system. This relationship suggests that adaptive chlorine dosing protocols should account for seasonal variations in TDS, which, in this study, ranged from 107 mg/L during the wet season (March) to 165 mg/L during the dry season (August–September).

The mechanism underlying the TDS–chlorine relationship potentially involves chlorine consumption by reduced species in higher-TDS water. During the dry season, when TDS increases due to reduced dilution and increased evaporation, source water may contain elevated concentrations of Fe^{2+}, Mn^{2+}, and dissolved organic matter, all of which exert chlorine demand. Water treatment facilities should consider implementing real-time TDS monitoring, coupled with automated chlorine dose adjustment to maintain consistent residual levels (0.2–0.5 mg/L as recommended by MoH Regulation No. 492/2010), throughout the distribution network.

The pH-TDS positive correlation observed at RM Bangil reflects the natural buffering capacity of carbonate-rich source waters. This relationship is beneficial from a water stability perspective, as higher TDS from alkaline species helps prevent corrosive conditions in distribution infrastructure. However, the concurrent negative pH-chlorine correlation at this site warrants attention. If this relationship reflects pH-dependent chlorine speciation (with more stable OCl^- at higher pH), utilities could optimize disinfection by targeting pH in the 7.5–8.0 range, where residual chlorine persistence is maximized while maintaining effective microbial inactivation.

3.4.2. Spatial heterogeneity in water quality processes

The differing patterns of significant correlations across the monitoring locations indicate clear spatial heterogeneity in the factors that influence water quality within the distribution system. For example, the TDS-chlorine relationship was observed at RM Winongan and RM Giri but was absent at RM Sidoarjo and Outlet Umbulan, even though the overall TDS ranges were broadly comparable. This variability suggests that several underlying processes may be operating differently across sites.

One possibility relates to differences in source water. Locations supplied by springs may have distinct dissolved constituent profiles compared with areas influenced by surface water infiltration, even when their TDS values fall within similar ranges. In particular, waters with higher organic carbon content tend to exert greater chlorine demand than those dominated by inorganic dissolved solids, potentially shaping the observed relationships.

Another contributing factor may be the characteristics of the distribution network. Variations in residence time between treatment and sampling points, differences in pipe materials, pipe age, and the extent of biofilm growth within the mains can all independently influence chlorine decay patterns of the source water's TDS. As a result, sites with similar feedwater chemistry may still exhibit different chlorine–TDS behaviors once the water moves through the network.

Differences in treatment processes across supply zones may also play a role. If specific monitoring sites receive water from different treatment facilities or if treatment intensity varies, the linkage between source water characteristics—such as TDS—and the quality of disinfected water, particularly residual chlorine, may differ accordingly. These combined factors help explain the spatial variability in correlations observed across the study area.

This spatial heterogeneity underscores the value of site-specific monitoring and management rather than applying uniform protocols across the entire distribution network. Sites showing stronger TDS–chlorine correlations (RM Winongan and RM Giri) may benefit from more frequent TDS monitoring and adaptive chlorine dosing. In contrast, more stable sites (RM Sidoarjo and Outlet Umbulan) may require less intensive parameter tracking.

3.4.3. Seasonal dynamics and climate change considerations

Although the correlation analysis examined parameter relationships across the entire year, the mechanisms identified have important implications for seasonal variability and potential climate change impacts. The TDS–chlorine relationship is particularly relevant given the pronounced seasonal TDS fluctuations observed in this study (107–165 mg/L).

During the wet season (monsoon period), dilution reduces TDS and may decrease chlorine demand, potentially allowing for lower chlorine doses while maintaining adequate residuals. Conversely, dry season conditions concentrate dissolved solids and increase chlorine demand, requiring dose adjustments. Under more extreme dry conditions, TDS could exceed the ranges observed in this study, potentially requiring substantial increases in chlorine dosing to maintain disinfection efficacy.

The pH-TDS relationship observed at RM Bangil also has implications for climate. If drought conditions further concentrate alkaline species, pH may rise above optimal levels (>8.5), potentially requiring pH adjustment for corrosion control and disinfection optimization. Conversely, extreme precipitation events could dilute buffering capacity, leading to pH instability and increased corrosion potential.

3.4.4. Statistical methodology and study limitations

The application of SRC rather than Pearson's product-moment correlation in this study requires a brief methodological discussion. Spearman's method was selected as most appropriate given: (i) a small sample size ($n = 12$ per site), (ii) high frequency of censored data (values below detection limits) for metal parameters, and (iii) no a priori assumption of linear relationships between parameters.

Several limitations must be acknowledged when interpreting these correlation results. First, correlation does not imply causation. Although the observed relationships align with established chemical principles discussed in the water quality literature, they represent statistical associations rather than confirmed cause-and-effect mechanisms. For example, the correlation between TDS and residual chlorine may arise from direct interaction between dissolved constituents and chlorine, from both variables responding simultaneously to an unmeasured factor such as seasonal variations in source water, from operational adjustments within the treatment process, or from a combination of these influences operating together.

Second, the small sample size limits statistical power. With monthly sampling (n = 12 per site), this study had 50–60% power to detect moderate correlations ($|\rho|$=0.5) at α = 0.05. Weak correlations ($|\rho|$<0.3) would rarely achieve statistical significance, increasing the risk of type II errors (false negatives). This explains why parameter pairs showing moderate correlation coefficients (e.g., ρ=−0.481 for TDS–Mn at RM Winongan) did not always reach statistical significance.

Third, the high proportion of censored data (values below detection limits) for metal parameters limited the assessment of metal-related correlations. Fe concentrations were below detection limits in approximately 83% of samples, Mn in 92%, and Al in 100% across all sites. When most observations are tied at the detection limit, rank-based correlation has minimal variation to assess, reducing the ability to identify relationships even if they exist.

Finally, temporal resolution constraints, where the monthly sampling protocol cannot capture short-term dynamics. Short-term changes in chlorine levels—such as daily fluctuations, transient contamination after rainfall, and adjustments in treatment operations—may not have been captured because monthly sampling cannot observe events occurring between scheduled sampling dates. The correlations we observed describe patterns on a monthly scale; therefore, they may miss relationships that actually play out over much shorter time intervals.

Despite these limitations, the significant correlations still offer meaningful insight into how the system works. The link between pH and TDS underscores the role of carbonate buffering in shaping the water chemistry. Meanwhile, the steady TDS–chlorine pattern seen across several locations shows that the amount of dissolved solids in the source water directly influences how effectively chlorine performs and how long the residual can be maintained. These insights translate into practical guidance for system operations and help point the way toward improvements in future monitoring efforts.

Future monitoring programs could enhance correlation detection by: (i) increasing sampling frequency to weekly or bi-weekly intervals, expanding sample size and improving temporal resolution; (ii) incorporating continuous sensors for parameters such as pH, turbidity, and residual chlorine to capture short-term dynamics; (iii) expanding the parameter suite to include dissolved organic carbon, temperature, and bacterial indicators; and (iv) extending monitoring duration to multiple years to distinguish systematic trends from interannual variability.

3.4.5. Contribution to SDG 6 monitoring framework

The correlation analysis contributes to SDG 6 by identifying parameter relationships relevant to drinking water safety and treatment optimization. The consistent TDS–chlorine relationship across multiple sites demonstrates that maintaining adequate disinfection—a core component of “safely managed” drinking water under SDG 6.1—requires accounting for natural variation in source water chemistry.

From an equity perspective, as emphasized in SDG 6 frameworks, the spatial heterogeneity in correlation patterns raises questions about whether different communities served by different monitoring sites experience equivalent water safety levels. Sites showing stronger chlorine demand (correlated with TDS) may be at higher risk of inadequate disinfection during periods of elevated TDS if treatment protocols do not account for this relationship. Ensuring that all communities—regardless of source water characteristics—receive adequately disinfected water requires site-specific management informed by the relationships identified in this analysis.

The absence of metal-related correlations in this study reflects the generally low and stable metal concentrations across all sites, which is positive from a public health perspective. However, the high proportion of non-detects also indicates that current analytical methods may have insufficient sensitivity to characterize trace-metal dynamics. For a more complete SDG 6 assessment, future studies should employ methods with lower detection limits or alternative indicators of metal exposure risk.

The findings of this study add to the broader international discussion on hydropolitics and the fair management of water resources, highlighting that access to clean water is not solely a technical issue but also shaped by social and political contexts. Viewed through a hydropolitical lens, patterns of water distribution reflect underlying power relations and policy choices across different regions.[69] In contrast, an equity-oriented perspective on water governance underscores the need for fair, inclusive, and participatory approaches in ensuring that water resources are managed and allocated responsibly.[70,71] Consequently, efforts to achieve SDG 6 at the local level must be incorporated into a governance framework that is just and transparent, ensuring that all communities have access to safe and sustainable water.

4. Conclusion

The aim of this study was to present an annual summary of drinking water quality at six important locations in the Umbulan distribution system in East Java. The results showed that throughout the monitoring period, *E. coli* and total coliform were consistently undetected, indicating that the water is in good microbiological condition at all sampling locations. The majority of chemical parameters—pH, TDS, Fe, Mn, Al, and residual chlorine—were within the limits established by the MoH. However, iron and residual chlorine concentrations showed brief, localized surges at a number of locations. These variations highlight the necessity for continuous monitoring, even though none of the excursions exceed national limits. Water quality varies throughout the network and is influenced by local hydrogeological features, infrastructure problems, and operational procedures. These findings suggest that site-specific dosage and monitoring systems should be developed rather than relying on a single standardized strategy across the entire system. This strategy can increase local involvement in achieving SDG 6, which emphasizes the provision of sustainable and clean drinking water. The monthly sampling strategy, modest sample size, and relatively high proportion of non-detects for specific metals represent important limitations of this study. Future studies are encouraged to use higher sampling frequencies, encompass a larger range of characteristics (e.g., dissolved organic carbon and temperature), and extend monitoring over multiple years.

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Conflict of interest

The authors declare they have no competing interests.

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Availability of data

The data used in this study are available from the corresponding author upon reasonable request.

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