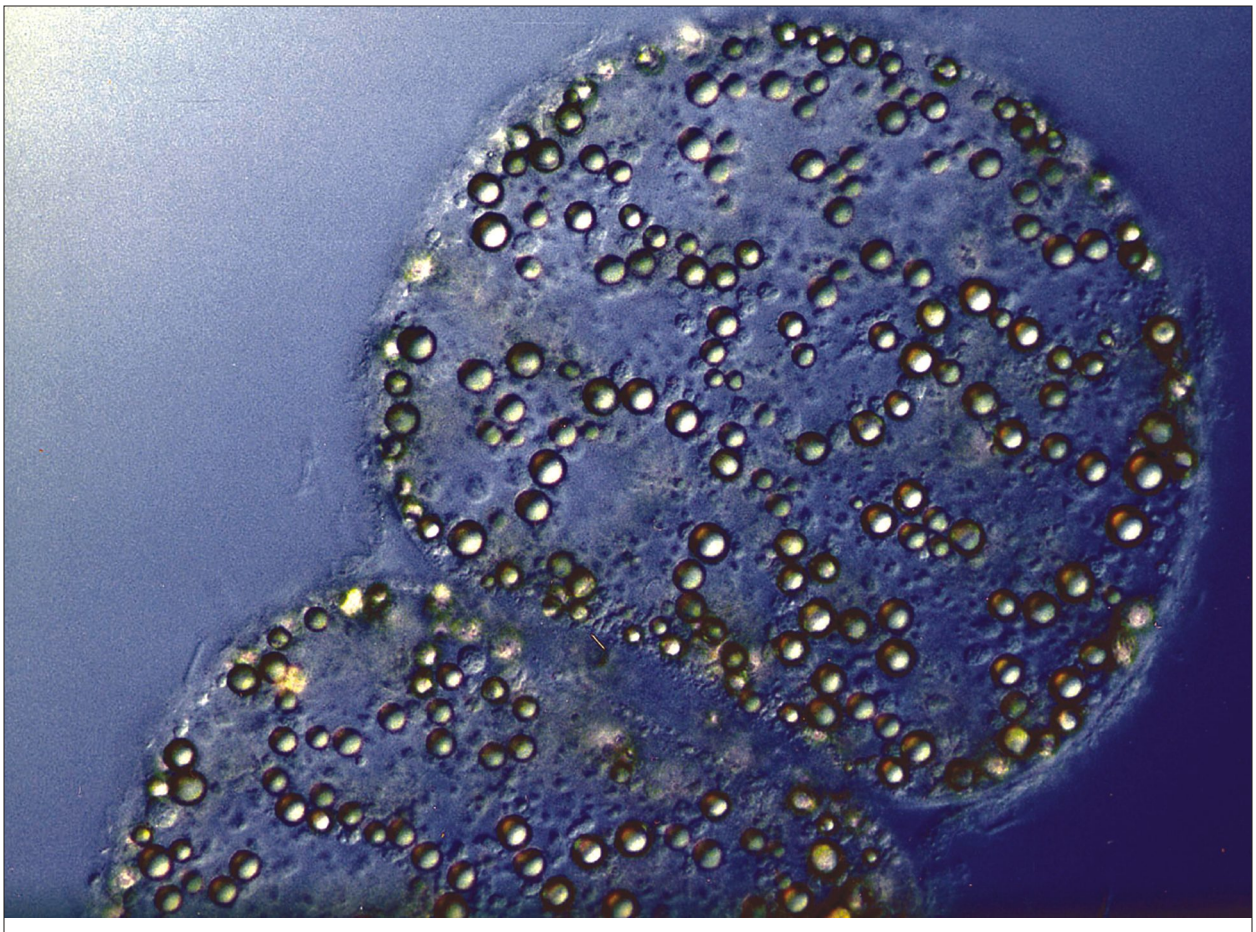

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Research Article
Variations in Bacteriological and Physicochemical Water Quality Characteristics of Asata River, Enugu, Nigeria

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Abstract

Background and Objective: Globally, river water remains an important source of water for drinking, domestic and other uses. This study aimed to assess the bacteriological and physicochemical properties of Asata River water. **Materials and Methods:** A total of 72 water samples were collected, over 12 months (September, 2017 to August, 2018), from six different sites along the river course, following standard methods. The physicochemical properties were determined *in situ* using appropriate measuring instruments. Total coliform counts (TCC) and *Escherichia coli* counts (EC) were determined using Chromocult Coliform Agar following the membrane filtration technique. Student's t-test statistic was used to compare the variations in mean values obtained during the rainy and dry seasons. **Results:** Temperature, total dissolved solids, pH and electrical conductivity had mean values ranging from 24.8-26.8°C, 10.8-20.1 mg L^{-1}, 4.0-7.1 and 15.8-29.5 µS cm^{-1}, respectively. Mean values of bacteriological parameters ranged from 5.0×10^{1}-5.9×10^{6} (TCC) and 1.0×10^{1}-4.6×10^{6} (*E. coli* counts). Bacterial counts in the rainy season were significantly higher ($p< 0.05$) than counts during the dry season. A significant correlation existed between EC and other water quality parameters, temperature, pH, TDS, *E. coli* and TCC. Bacteriological properties were high and beyond the acceptable standard limits. **Conclusion:** Asata River water quality is poor and may constitute a serious public health risk if used without treatment. Adequate provision and use of suitable sanitary infrastructure will help protect this water source from further faecal contamination.

Key words: Water quality, river water, faecal contamination, public health, coliform

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Water is essential for most human activities including hygiene, general health and total well-being of individuals, communities and nations. As a result, access to safe drinking water is regarded as a fundamental human right and has also, become an issue of global concern[1]. The United Nation's Sustainable Development Goal (SDG) No. 6, "ensuring availability and sustainable management of water and sanitation for all" aims at achieving universal and equitable access to safely managed and affordable drinking water for all, by the year 2030. Safely managed drinking water can be defined as a better source of drinking water that is on-site, available when needed, free of faecal matter and prioritized chemical contaminants such as nitrate, nitrite and cyanide contamination[2].

Despite efforts at meeting SDG No 6, access to safely managed drinking water is still limited in most developing countries[2]. Thus, compelling many rural and suburban communities and low-income earners to resort to unsafe water sources, including surface water, for drinking and other purposes. For instance, the 2017 update on SDG progress on drinking water, sanitation and hygiene reported that 844 million people worldwide lack basic drinking water services and 58% of people who live in Sub-Saharan African (SSA) collect drinking water directly from surface water sources[2].

Surface waters are exposed to pollution from point and non-point sources. Over 80% of wastewater from human activities is discharged into surface water without treatment[3]. Yet, these surface water sources still serve for drinking, cooking and food processing, hygiene, recreation and irrigation of fresh produce in SSA[4-6]. Consequently, surface waters are vulnerable to contamination with faecal matter, priority chemicals and heavy metals and, their quality varies between time and space. Localized monitoring of surface water is recommended to avert outbreaks of water-borne diseases[7].

Monitoring surface water involves assessing the physicochemical and bacteriological water quality parameters and comparing the findings with the acceptable laid down standards and guidelines for safe drinking water[8]. Physicochemical water quality parameters include, but are not limited to pH, temperature, water conductivity, total dissolved solids, biochemical oxygen demand and the presence of some inorganic compounds and heavy metals. Although some of these physicochemical parameters do not have any direct health impact, they are important assessment parameters to ensure that water is safe for use. This is because they determine many chemical and biological processes in water. Further, when their values are beyond the acceptable limits, they constitute a problem for water treatment and water distribution system[8].

Globally, monitoring the bacteriological quality of water involves the use of indicator organisms such as coliform (*E. coli*, total coliform and faecal coliform) and *Enterococcus*[8]. The detection of bacterial indicators in surface water signifies faecal contamination and the potential presence of enteric pathogens[9]. The presence of pathogens in water is associated with waterborne diseases such as diarrhoea[9,10]. Diarrhoea contributes significantly to the global disease burden and is the fourth leading cause of death in children under the age of 5 years[10]. People using faecally contaminated water are at risk of infection with enteric pathogens. Further, waterborne diseases can be transmitted among people who use the water for drinking and domestic activities[11], recreation[12] and irrigation of fresh produce[13]. In addition to the distribution of pathogens and their associated diseases, faecally contaminated surface water has been reported to harbour multiple drug resistance (MDR) bacteria[12,14,15]. MDR bacteria constitute other serious public health risks such as the dissemination of antibiotic resistance markers to previously susceptible strains or species in the aquatic environment[16,17]. Infection with MDR organisms results in treatment failure, leading to diseases with high morbidity and mortality.

Asata River, located in Enugu-Urban is important as a source of water for domestic, industrial and irrigation uses, as well as for recreational purposes in the proximal community. Being an important source of water, some sites along the river basin were marked for the "Water quality mapping project of the Enugu State Ministry of Environment". Some studies have reported from the environmental point of view, the hydrogeochemical and physicochemical water quality of the river[18]. A few studies assessed the effect of urban waste[19] and the impact of human activities[20] on the quality of the river. Other studies determined the pollution level[21] and heavy metal concentration[18] of the river. However, none of the aforementioned studies assessed the bacteriological quality of the river on an annual scale, over time (seasons) and space (locations). Besides, it is of public health importance to regularly monitor and assess the bacteriological quality of an important surface water body which serves for public use.

This study aimed to quantitatively assess variations in the bacteriological and selected physicochemical quality parameters of Asata River water.

MATERIALS AND METHODS

Study area and sample collection: Asata River is one of the two main rivers that drain through Enugu urban. Enugu urban is the capital of Enugu State in Nigeria and comprises three local government areas, Enugu North, Enugu South and Enugu East. Enugu has a population of about 816,000 people (https://worldpopulationreview.com/world-cities/enugu-population) and is located on longitude 7°30'53.5"E-7°34'40.54"E and latitude 6°24'14.62"N-6°24'26.94"N and on the altitude of 152 m above sea level[22]. Enugu urban has a tropical wet climate, with a mean temperature of 27°C and rainfall of about 1500-2100 mm. The wet season in Enugu lasts for about 7-8 months. The meteorological data of over 96 years indicate that intense rainfall starts in March and ceases in October[22]. In this study, 8 months (March to October) were designated as the rainy season and 4 months (November to February) as the dry season because rainfall started in late February and a very heavy downpour occurred on our designated sampling day in March, 2018.

River Asata is a perennial river with a length of about 19.8 km[18], having other streams like the Idaw River to feed it. It emanates from the shallow aquifers of Udi Hills and drains through major densely populated areas of colon, Coal-Camp, Uwani, Obiagu, Asata, Independence Layout, New Heaven extension and empties into the other major river, the Ekulu River, at Obinagu, Emene. Asata River is heavily impacted by anthropogenic activities such as open defecation, compost manure run-offs, herd watering, untreated effluents discharge (from abattoir, food and livestock markets), sewage effluents (from the household, hospital and industrial sites within its vicinity) and heavy refuse dumps.

A total of six sampling sites, S1-S6 were selected along the river course based on access, anthropogenic activity, major water use and dense human settlement/non-human settlement. The geo-coordinates of the sampling points were determined using a GPS navigator. The sampling sites are described and presented in Table 1.

Following standard methods, water samples were collected from each of the six sampling sites using 250 mL sterile glass bottles. Samples were collected once every month from September, 2017 to August, 2018, between the 1st and 2nd week of the month and transported in an ice chest box to the laboratory for analysis. Water samples were analysed in triplicates within 6 hrs of sample collection. In all, a total of 72 samples (water samples from 6 sites for 12 months) were collected and analyzed.

Physicochemical quality assessment: Physicochemical water quality parameters (pH, temperature, conductivity and total dissolved solids) were determined *in situ*, according to standard methods. The appropriate measuring meters were used: The pH (pHep® pocket-sized pH meter [HANNA HI-98107, USA]), temperature (mercury-in-glass environmental thermometer) and conductivity and TDS (DiST Conductivity/TDS meter [HANNA HI-98107, USA]) following the manufacturer's instructions after standardization of the instruments.

Enumeration of bacteriological water quality indicators: The bacteriological quality of the water samples was determined using the membrane filtration (MF) method. MF has the advantage of being flexible to the amount of sample filtered and as well, permits specific quantification[23]. Total coliform and *Escherichia coli* counts were determined by plating the membrane filter on chromocult coliform agar (CCA) (Merck, Germany). The CCA, with its combination of two chromogenic substances, can specifically and simultaneously detect *E. coli* and total coliforms based on specific colony colours[24]. Each of the 72 samples was analysed in triplicates.

Ten fold serial dilution of the water samples was performed using sterile distilled water. A 100 mL dilution of the water samples was filtered through a 0.45 µm membrane filter (Millipore, Merck, Germany) coupled to a vacuum pump. After filtration, the membrane filter was aseptically placed on a sterile freshly prepared and dried CCA plate. Incubation was carried out aerobically at 35°C for 24 hrs after which all typical colonies were counted. Typical colonies appearing blue to violet were counted as *E. coli* while colonies appearing salmon (pink) to red were counted as other coliforms. Total coliform consists of all blue to violet (*E. coli*) and salmon to red (other coliforms) colonies[24]. Counts were reported as colony-forming units per 100 mL (CFU 100 mL^{-1}). A few colonies were selected based on characteristic cultural morphology, isolated and identified microscopically and biochemically.

Statistical analysis: Data collation and plotting of charts were carried out using Microsoft Excel, 2010 software. All statistical analyses were performed using SPSS version 20 software. Significance was recorded at a $p<0.05$ confidence level. Results were presented in Mean±Standard error from the triplicate results of physicochemical values and bacterial counts. The ANOVA and *post hoc* (Duncan's Multiple Range

Table 1: Sample points coordinates and description of sampling sites

Sampling sites (coordinates)	Description/remarks
S1: Recreation Point (S1_RP) (Lat: 6°26'2.977"N, Lon: 7°27'50.435"E)	At this point, the water trickling from the river source has expanded. There are no human residence near it but, recreational activity (children swimming) and fresh produce irrigation occur here
S2: Coal Camp Bridge (S2_CCB) (Lat: 6°25'59.303"N, Lon: 7°28'30.935"E)	Located within a densely human settlement and is characterized by intense domestic refuse disposal, point source sewage discharges, high level of open defecation and river bank farming activities. It is designated as sampling station for "water quality mapping project for Enugu metropolis (EMENV008)"
S3: Zik's Avenue Bridge (S3_ZAB) (Lat: 6°26'10.248"N, Lon: 7°29'40.092"E)	This site is located downstream of "Akwata Market-Ogbete", where all manner of wastes are indiscriminately dumped along its channel. It has observable open defecation activities, refuse dumping, run-off from mechanic workshop, metal dumps and car washing activities. Additionally, major drains from residential areas are emptied here
S4: Presidential Road (S4_PR) (Lat: 6°26'35.13"N, Lon: 7°30'5.12"E)	S4 is affected by high open defecation activities and waste water discharge from sub-urban residential settlement within its vicinity. Run-off and possible waste disposal from the general hospital located within its vicinity was observed. The rock within the Asata River catchment provides a major source of water for drinking and domestic uses to the resident of the area
S5: EN-PH Road Bridge (S5_ERB) (Lat: 6°27'18.36"N, Lon: 7°32'23.136"E)	This site is located beneath the Enugu-Port Harcourt express way bridge. It provides a source of water for washing of food items, bathing, car washing and water abstraction for tanker vendor supply. It receives run-off water from car washes, agricultural farm. Downstream of it harbours a livestock market and its abattoir effluents are directly discharged into it without any form of treatment
S6: Before Ekulu-Asata Confluence (S6_BEC) (Lat: 6°44'30.92"N, Lon: 7°50'14.21"E)	Less human presence however, is a site for herd watering and grazing and irrigation for fresh produce

NB: Sites were mapped using GPS compass navigator

Test) were used to statistically compare differences in the mean between sampling sites. A test for significant differences between water quality parameters during the rainy and dry seasons was performed using the student's t-test statistic. Pearson correlation statistic was used to determine the relationship between water quality parameters.

RESULTS

The results of the physicochemical water quality properties are presented in Table 2. It reveals that temperature ranged from 24.8-26.8°C at S1 and S6, pH ranged from 4.0-7.1 at S1 and S6, total dissolved solids range from 10.8-20.1 mg L^{-1} at S1 and S4, electrical conductivity ranged from 15.8-29.5 µS cm^{-1} at S1 and S4, respectively. Variations exist on the spatial scale with a significantly higher value recorded at S4 for TDS and EC, respectively.

The result of seasonal variation in physicochemical water quality of Asata River reveals that at the spatial level, temperature values were not significantly different between seasons (rainy and dry). As in Table 3, the rainy season temperature ranged from 27.4-25.3°C while it ranged from 26.2 and 24.2°C in the dry season. Similarly, the pH values ranged from 6.94-4.17 and 7.41 and 3.86 in the rainy and dry seasons, respectively. Significant variations were recorded in the mean seasonal pH values at sites S3, S4, S5 and S6.

The result of monthly variation for bacterial counts in Fig. 1 shows that about 10000 CFU 100 mL^{-1} of *E. coli* and total coliform were recorded in the dry season (November, 17 to February, 18) whereas higher counts, above 100000 CFU 100 mL^{-1} were recorded in the rainy season (September and October, 17 and March to August, 18). Spatial variation in the mean concentration of faecal indicator bacteria at the six sites reveals that total coliform counts were above 2-fold higher than *E. coli* counts in Fig. 2. Except for S1 which had bacterial counts below 10000 CFU 100 mL^{-1}, all other sampling sites (S2-S6) recorded counts above 10000 CFU 100 mL^{-1} (Fig. 2). The concentrations of bacterial counts were significantly higher at S2 than at all other sampling sites.

The findings presented in Table 4 indicate that *E. coli* counts were higher (2.4×10^5 CFU 100 mL^{-1}) during the rainy season than in the dry season (8.3×10^3 CFU 100 mL^{-1}). The same trend was observed for total coliform, where the rainy season count was 6.2×10^5 and the dry season count was 3.2×10^4 for all river water samples collected per season. The obtained differences in bacterial counts were statistically higher in the rainy season for all river water samples collected per season (Table 4). Only a few bacteria genera were isolated and identified in this study and the result is presented in Table 5. Identified isolates include *E. coli*, *Citrobacter* spp. and *Salmonella* spp.

The result of pearson correlation statistics between water quality parameters as presented in Table 6 shows that a significant positive correlation ($p<0.01$) exists between electrical conductivity and all other water quality parameters (*E. coli*, 0.193, total coliform, 0.249, pH, 0.383 and total dissolved solids, 1.00) and also with water temperature (0.145) at $p<0.05$ (Table 6).

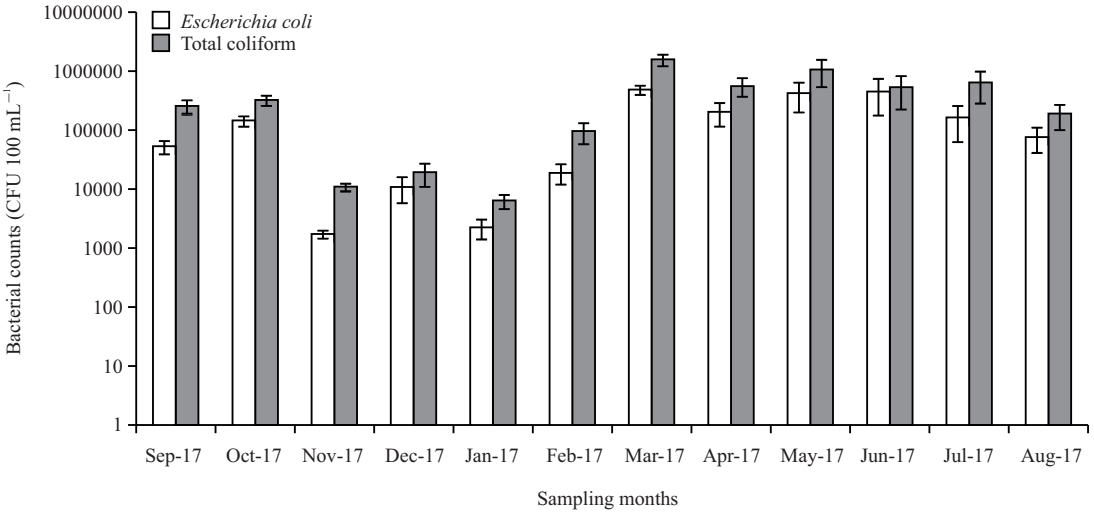

Fig. 1: Monthly variations in mean values of bacteria indicators of faecal pollution in the Asata River
Standards: *E. coli*: NSDWQ, zero CFU 100 mL^{-1} and WHO_GDWQ, zero CFU 100 mL^{-1}, Total coliform: NSDWQ, 10 CFU mL^{-1} = 1000 CFU 100 mL^{-1} and WHO_GDWQ, NA

Table 2: Spatial variations in the physicochemical characteristics of the Asata River

		Physiochemical properties (Mean±SE)			
Sampling sites*		Temperature (°C)	pH	TDS (mg L^{-1})	EC (µS cm^{-1})
S1	(Mean±SD)	24.8±0.26^{a}	4.0±1.2^{a}	10.8±0.4^{a}	15.8±0.6^{a}
	Range	20.0-28.0	3.3-6.3	6.0-14.0	8.8-20.6
S2	(Mean±SD)	25.0±0.32^{a}	6.5±0.9^{b}	15.1±0.5^{c}	22.2±0.7^{c}
	Range	20.0-28.0	5.3-7.3	11.0-21.0	16.2-30.9
S3	(Mean±SD)	25.5±0.33^{ab}	6.9±0.4^{c}	16.3±0.5^{c}	24.0±0.8^{c}
	Range	20.0-29.0	6.4-7.3	11.0-22.0	16.2-32.4
S4	(Mean±SD)	26.0±0.28^{bc}	7.0±0.5^{c}	20.1±0.5^{d}	29.5±0.8^{d}
	Range	21.0-29.5	6.5-7.5	12.0-24.0	17.6-35.3
S5	(Mean±SD)	26.5±0.30^{c}	7.0±0.5^{c}	15.7±0.3^{c}	23.1±0.4^{c}
	Range	21.0-29.0	6.7-7.6	12.0-18.0	17.6-26.5
S6	(Mean±SD)	26.8±0.34^{c}	7.1±0.6^{c}	13.7±0.4^{b}	20.1±0.6^{b}
	Range	20.0-29.5	6.8-7.7	10.0-17.0	14.7-25.0

WHO/NSDWQ Standards: Temperature, ambient, pH, 6.5-8.5, TDS, 500 mg L^{-1}, EC, 1000 µS cm^{-1}, *for each sampling site parameter, means with different letters (superscripts) are significantly different (p<0.05) using Duncan's Multiple Range Test, SE: Standard error, °C: Degree celsius, TDS: Total dissolved solids, mg L^{-1}: Milligram/litre, EC: Electrical conductivity of water and µS cm^{-1}: Micro siemens per centimetre

Table 3: Seasonal variation in physicochemical water quality of the Asata River at sampling sites (S1-S6)

	Water temperature (°C)		pH		Total dissolved solids (mg L^{-1})		Electrical conductivity (µS cm^{-1})	
Sampling sites	Rainy season* (Mean±SE)	Dry season* (Mean±SE)	Rainy season* (Mean±SE)	Dry season* (Mean±SE)	Rainy season* (Mean±SE)	Dry season* (Mean±SE)	Rainy season* (Mean±SE)	Dry season* (Mean±SE)
S1	25.3±0.1^{a}	24.2±0.6^{a}	4.17±0.20^{a}	3.86±0.06^{a}	10.24±0.65^{a}	11.53±0.34^{a}	15.04±0.96^{a}	16.95±0.49^{a}
S2	25.6±0.1^{a}	24.2±0.7^{a}	6.45±0.09^{a}	6.53±0.18^{a}	16.05±0.69^{a}	13.80±0.43^{b}	23.60±1.01^{a}	20.29±0.63^{b}
S3	26.0±0.2^{a}	24.7±0.7^{a}	6.80±0.30^{a}	7.03±0.08^{b}	17.33±0.79^{a}	14.93±0.28^{b}	25.50±1.16^{a}	21.97±0.42^{b}
S4	26.2±0.2^{a}	25.6±0.6^{a}	6.90±0.05^{a}	7.12±0.09^{b}	21.10±0.54^{a}	18.60±0.88^{b}	31.03±0.79^{a}	27.35±1.30^{b}
S5	27.0±0.2^{a}	25.9±0.7^{a}	6.92±0.04^{a}	7.21±0.08^{b}	15.95±0.24^{a}	15.40±0.50^{a}	23.45±0.36^{a}	22.64±0.73^{a}
S6	27.4±0.1^{a}	26.2±0.8^{a}	6.94±0.02^{a}	7.41±0.10^{b}	13.61±0.46^{a}	13.73±0.66^{a}	20.02±0.68^{a}	20.19±0.98^{a}
All river water sample collected per season	26.1±0.09^{a}	25.0±0.34^{b}	6.4±0.09^{a}	6.5±0.16^{b}	15.2±0.35^{a}	15.4±0.34^{a}	22.4±0.51^{a}	22.6±0.50^{a}

*Means with different superscripts (letters) are significantly difference (p<0.05), using student's t-test, **SE: Standard error, **Rainy season = 8 months and Dry season = 4 months

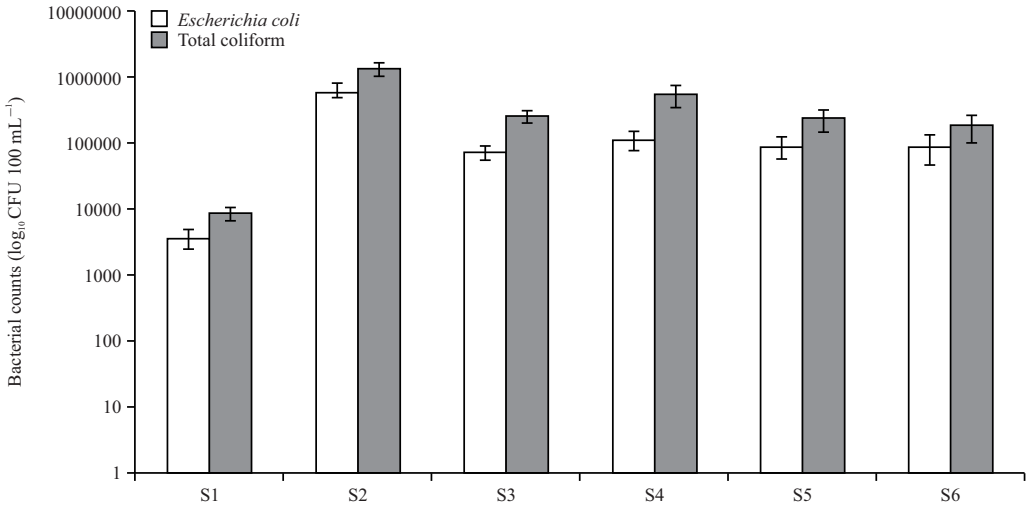

Fig. 2: Spatial variation in mean concentrations of faecal indicator bacteria at the six sites (S1-S6) located on the Asata River
Standards: *E. coli*: NSDWQ, zero CFU 100 mL^{-1} and WHO_GDWQ, zero CFU 100 mL^{-1}, Total coliform: NSDWQ, 10 CFU mL^{-1} = 1000 CFU 100 Ml^{-1} and WHO_GDWQ, NA

Table 4: Seasonal variation in bacteriological water quality of the Asata River at sampling sites (S1-S6)

	Escherichia coli (CFU 100 mL^{-1})		Total coliform (CFU 100 mL^{-1})	
Water sample sites	Rainy season* (Mean±SE)	Dry season* (Mean±SE)	Rainy season* (Mean±SE)	Dry season* (Mean±SE)
S1	$5.6\times10^{3}\pm1.9\times10^{3a}$	$9.5\times10^{2}\pm3.7\times10^{2a}$	$1.1\times10^{4}\pm3.0\times10^{3a}$	$5.2\times10^{3}\pm1.7\times10^{3a}$
S2	$1.1\times10^{6}\pm2.6\times10^{5a}$	$3.3\times10^{4}\pm0.1\times10^{3b}$	$2.2\times10^{6}\pm4.4\times10^{5a}$	$1.0\times10^{5}\pm3.9\times10^{4b}$
S3	$7.8\times10^{4}\pm2.1\times10^{4a}$	$6.1\times10^{4}\pm3.2\times10^{4a}$	$3.5\times10^{5}\pm8.3\times10^{4a}$	$1.2\times10^{5}\pm5.7\times10^{4b}$
S4	$1.6\times10^{5}\pm5.8\times10^{4a}$	$4.8\times10^{4}\pm2.1\times10^{4a}$	$8.3\times10^{5}\pm3.1\times10^{5a}$	$1.2\times10^{5}\pm4.2\times10^{4a}$
S5	$1.2\times10^{5}\pm5.8\times10^{4a}$	$4.8\times10^{4}\pm2.5\times10^{4a}$	$3.0\times10^{5}\pm1.4\times10^{5a}$	$1.4\times10^{5}\pm7.1\times10^{4a}$
S6	$1.4\times10^{5}\pm7.2\times10^{4a}$	$1.6\times10^{4}\pm8.1\times10^{3a}$	$2.8\times10^{5}\pm1.4\times10^{5a}$	$4.3\times10^{4}\pm2.1\times10^{4a}$
All river water samples collected per season	$2.4\times10^{5}\pm4.9\times10^{4a}$	$8.3\times10^{3}\pm2.2\times10^{3b}$	$6.2\times10^{5}\pm1.0\times10^{5a}$	$3.2\times10^{4}\pm9.9\times10^{3b}$

*For each sampling site season, having means with different superscripts (letters) are significantly different (p<0.05), using the student's t-test, SE: Standard Error, **Rainy season = 8 months and Dry season = 4 months

Table 5: Characterization of coliform bacteria from Asata River

Colony colour on CCA	Gram reaction	Salmon-GAL	X-Glucuronide	Indole	Catalase	Methyl red	Oxidase	Organism
Dark-blue to violet	-ive rod	+	+	+	+	+	-	*E. coli*
Salmon to red	-ive rod	+	-	-	+	+	-	*Citrobacter*
Colourless	-ive rod	-	-	-	+	+	-	*Salmonella*

Table 6: Correlation half matrix of Asata River water quality

	Pearson's correlation coefficient					
Parameters***	*E. coil*	TC	Temperature	pH	TDS	EC
E. coli (CFU 100 mL^{-1})	1					
TC (CFU 100 mL^{-1})	0.770**	1				
Temperature (°C)	0.052	0.071	1			
pH	0.019	0.062	0.128	1		
TDS (mg L^{-1})	0.193**	0.249**	0.145*	0.383**	1	
EC (µS cm^{-1})	0.193**	0.249**	0.145*	0.383**	1.000**	1

Pearson correlation coefficients: **Correlation is significant at the p<0.01 level, *correlation is significant at p<0.05 level, TC: Total coliform count, TDS: Total dissolved solids and EC: Electrical conductivity

The result presented in Table 7 compares Asata River water quality with given water quality standards and guidelines. The pH quality of Asata River (6.4) was slightly below the laid down standard pH, 6.5-8.5. As for the bacteriological qualities (*E. coli* and total coliform), Asata River quality for *E. coli* was 1.7×10^{5} CFU 100 mL^{-1} whereas, FGN/SON and WHO standards recommend zero *E. coli* for drinking water. Although, FGN/SON recommended about

Table 7: Comparison of Asata River properties with stipulated water quality standards and guidelines

		Drinking water standard			Other standards
Parameters	Asata River quality*	FGN/SON	WHO	EPA	Irrigation and abstraction
Temperature (°C)	25.8	Ambient	Ambient	NA	NA
pH	6.4	6.5-8.5	6.5-8.5	6.5-8.5	6.5-8.5
Total dissolved solids (mg L^{-1})	15.3	500	600-1000	500	450-2000
Electrical conductivity (µS cm^{-1})	22.5	1000	1000	NA	1000
E. coli (CFU 100 mL^{-1})	1.7×10^5	Zero	Zero	NA	NA
Total coliform (CFU 100 mL^{-1})	4.2×10^5	1000	NA	Zero	1000[a]/ 5000[b]

References: (FAO, 2012, FGN/SON, 2015, USEPA, 2018, WHO, 2017), *Quality was determined from a total of 72 (6 sites by 12 months) water samples from Asata River basin, NA: Not available, a: Irrigation water and b: Water for abstraction

1000 CFU 100 mL^{-1} for total coliform, EPA stipulates zero total coliforms but, Asata River quality recorded total coliform value of 4.2×10^5 CFU 100 mL^{-1}. A number that is higher than the standard for irrigation water (1000 CFU 100 mL^{-1}) and water for abstraction (5000 CFU 100 mL^{-1}) (Table 7).

DISCUSSION

The mean temperature values (24.8-26.8°C) in this study are a reflection of the ambient temperature at the time of sampling. Such temperature ranges have been reported in similar studies[18,19] and are typical of Enugu tropical wet climate temperature[22]. The pH of water is an important parameter to assess water quality. It stipulates the degree of acidity, controls other processes (physical, chemical and biological) such as the dissolution of toxic heavy metals, the survival of some group of microorganisms and determines the extent of pollution in a water body[6,25].

The pH of the Asata River was acidic to slightly alkaline, having an acidic range of 3.3-6.3 at S1 and a slightly acidic to alkaline range (6.8-7.7) at S6. Except for S1, with a mean acidic pH (4.0), all other sites had slightly acidic to alkaline pH values within the standard permissible limit (6.5-8.5). The water from a site (S1) may not be safe for recreational activities since a pH below 4.0 has been reported to cause redness of the eye and irritation[8]. The low pH observed at S1 could be attributed to the rock composition. However, another study ascribed the acidic pH observed at that sampling point to be an outcome of the acid mine drainage[18]. Total dissolved solids (TDS) and electrical conductivity (EC) were high at S4, with a significantly higher value than at other sampling sites (Table 2). The site (S4) is located at the heart of Enugu, with a high human presence and activities. The urban slum within the vicinity feeds the river with all sorts of effluent/wastewater from household activities. Again, effluent from a State General Hospital makes its way into the river and there is an intense car washing activity whose effluent drains directly into the river about the site (S4). On the other hand, sites (S1 and S6) with less human presence/settlement had lesser TDS and EC values. Previous studies agree with this finding and reported increased TDS values at sites located in urbanized areas than sites away from urbanized areas[19]. Nevertheless, the values observed in this study were below the maximum permissible limit for safe drinking water[8,26].

The present study observed seasonal variation in parameters studied which aligned with previous studies. Akoachere *et al.*[27], reported a non-significant difference in temperature between sample sites. Similarly, in assessing seasonal variability of water quality indices in the Democratic Republic of Congo, a higher (more alkaline) pH was observed during the dry season than in the rainy season[25]. This coincides with the findings in this research as significantly higher pH values were recorded at sites (S3-S6).

The presence/absence of bacteria indicators is basic to the microbiological quality of any water. Regrettably, bacterial counts, both *E. coli* and total coliform in this study were above 1000 CFU 100 mL^{-1} in all the sampling months. The peak bacterial counts observed in March attest to the impact of rain storms on river water quality, as there was a heavy downpour on the sampling day in March.

For all six sampling sites (S1-S6), bacterial counts were above the permissible limit of zero CFU 100 mL^{-1} for *E. coli* and 1000 CFU 100 mL^{-1} for total coliform[26]. The WHO standard for drinking water stipulates zero coliforms in 100 ml of water, be it, *E. coli*, total coliform, or faecal coliform[8]. But, the Nigeria standard for water quality stipulates zero *E. coli* in 100 mL of water and not more than ten total coliform per mL of water. That is, approximately 1000 CFU 100 mL^{-1} for total coliform[26]. Further, the WHO standard limit for unrestricted irrigation water (that is, water used for the irrigation of fresh produce, crops that are eaten uncooked) is <1000 CFU 100 mL^{-1} and, the European Union gave a total coliform limit of <5000 CFU 100 mL^{-1} for surface water used for raw water abstraction (that is, water for full physical and chemical treatment with disinfection)[6,13].

The result obtained in this study indicates that all 72 water samples did not meet the total coliform standards for drinking water (less than 1 CFU 100 mL^{-1}), water for irrigation (less than 1000 CFU 100 mL^{-1}) and raw water for abstraction (5000 CFU 100 mL^{-1}). Based on the aforementioned, Asata River water quality is poor and not suitable for drinking, domestic uses or fresh produce irrigation without prior treatment. The high bacterial counts as recorded in this study are an indication of continual faecal contamination. This finding is worrisome as high *E. coli* counts may pose a public health risk of contracting urinary tract infection, bacteraemia, meningitis, diarrhoea and other water-borne diseases to those who use the water for bathing, recreation, drinking and food processing without prior treatment[26]. At S2, bacterial counts were very high, above 6×10^5 and 1×10^6 CFU 100 mL^{-1} for *E. coil* and total coliform, respectively. It is not surprising as the site, observably, receives continuous effluent from sewage pipes and direct sewage discharge from dilapidated septic tanks. It is also a site with a high level of litter, where all sorts of refuse and waste (including, human waste) are discarded. Evidence of open defecation was also high and this probably was responsible for the high bacterial counts recorded at site S2. On the contrary, bacterial counts were least at site S1, which had a significantly lower count compared to counts at the other sampling sites. The site (S1) is located towards the river mouth, coinciding with the report that water quality is usually better towards the mouth of a river and may degrade along the water course[6].

Although the observations at some sites were comparable, significantly higher bacterial counts were recorded at S2 for *E. coli* and at S2 and S3 for total coliform during the rainy season than in the dry season. Furthermore, significantly higher mean counts were obtained during the rainy season for all water samples collected per season for both *E. coli* and total coliform. According to previous reports, in Enugu metropolis wastes released into drainages during rainfall empty into surface waters that cut across the Enugu urban[28]. Again, Singh *et al.*[29], reported that coliform contamination is higher during the rainy season while the high rainfalls during the rainy season sometimes lead to overflow of sewage systems and subsequent breakdown of overall hygiene standards[30].

The concentration of *E. coli* that was recorded in this study is a cause for concern. Although some *E. coli* strains are considered commensals, pathogenic ones abound in freshwater bodies, which are capable of causing a wide range of human diseases[31]. Research reports showed that human diseases occurring from infections with *E. coli* result in about 2 million deaths yearly[32]. The detection of *Salmonella* and *Citrobacter* is a confirmation of faecal contamination and the possible presence of pathogens. *Citrobacter* is responsible for urinary tract infections and can cause healthcare-related infections in children and the immunocompromised. *Salmonella*, on the other hand, causes severe gastroenteritis and other systematic diseases such as typhoid and paratyphoid fever.

Electrical conductivity showed a significant correlation with all assayed water quality parameters. This observation was in line with previous findings, reporting a correlation between electrical conductivity and all other parameters of water quality[9]. Also, Eliku and Leta[33] reported a strong positive correlation between pH and electrical conductivity. Further, a significant correlation (0.77) occurred between *E. coil* and total coliform in this study. This goes to buttress the point that both organisms are enteric and indicates faecal contamination, such that where one is present, the other is likely to exist.

The comparison of Asata River water properties regarding acceptable standards showed that the physicochemical properties were within the safe limit except for pH (6.4). However, bacteriological properties were far above the acceptable limit (Table 7). According to water quality guidelines and standards, physicochemical parameters (temperature, pH, TDS and EC) do not have any direct health implications, rather, they affect treatment and water distribution processes[8,26]. While the concentration of total coliform beyond the maximum permissible limit indicates faecal contamination, the presence of *E. coli* in water poses a potential public health hazard of human diseases such as urinary tract infections, bacteraemia, meningitis, diarrhoea, acute renal failure and haemolytic anaemia[26].

CONCLUSION

The high bacterial counts reported indicate severe faecal contamination and possible health risk of waterborne diseases from the use of Asata River water. Significant variations were identified in the water quality of the Asata River both spatially and seasonally. Although some physicochemical parameters were within the permissible limits, bacterial indicators were extremely high and unacceptable for water used for drinking, domestic purposes and irrigation of crops eaten uncooked. Asata River water quality is poor and may constitute a serious public health hazard when used without proper treatment. Public health education, targeted toward sanitary consciousness and source water protection is recommended. Further research could focus on assessing, the incidences of waterborne pathogens of public health importance.

SIGNIFICANCE STATEMENT

This is the first study to assess the bacteriological quality of the Asata River on an annual scale, over time (seasons) and space (locations). Further, the study monitored and assessed the bacteriological quality of Asata which is important to public health.

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