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EVALUATION OF A DEVELOPED WATER QUALITY MONITORING SYSTEM (WQMS) ALONGSIDE WEIGHTED ARITHMETIC WATER QUALITY INDEX MODEL

Eganoosi ESME ATOJUNERE [1]✉, Glory Ayodele OGUNLEYE [2]

[1] *Department of Soil Science and Biosystems Engineering, College of Agriculture, Fisheries and Forestry, Fiji National University, Nasinu, Fiji Islands*
[2] *Department of Systems Engineering, Faculty of Engineering, University of Lagos, Akoka, Nigeria*

Highlights:
- Pollution of water sources is on the rise from natural and anthropogenic sources globally;
- Current method for water pollution detection is expensive and time consuming;
- WQMS was developed and tested based on the Water Quality Index of 5 water quality indicators;
- Statistical analysis indicated high correlation among all the parameters examined, an indication of the versatility of the WQMS;
- The WQI values for well water, rainwater, Neimeth water, and River Ogun water values below the WQI threshold of 25 whereas seawater was 26 to 50 indicating its reliability with WHO standard.

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Abstract. Measurement of the quality of water before usage is important; however, this is challenging in developing countries, where water testing equipment is expensive and inaccessible. A Water Quality Monitoring System (WQMS) was developed to ease these unsafe water usage practices and improved water quality monitoring and data management. WQMS consisted of 5 different water quality sensors built on Arduino microprocessors to measure multiple water quality parameters, pH, EC, TDS, temperature and turbidity values simultaneously. Water samples from 5 sampling points S_1, S_2, S_3, S_4, and S_5 along River Ogun, Nigeria were tested and their Water Quality Status (WQS) was calculated using the Weighted Arithmetic Water Quality Index. WQMS has 78% efficiency and able to measure multiple WQIs. All studied parameters were significantly different, probably attributed to WQMS calibration methods and sensor performances. The WQS of the sampled water ranged from 26 to 50, which, according to standards, was within good water quality.

Keywords: sensors, water quality monitoring, parameters, efficiency.

✉Corresponding author. E-mail: *eganoosi.atojunere@fnu.ac.fj*

1. Introduction

Water is facing a decline in quality due to several natural forces and human-driven factors (Magesh et al., 2013). The hydrology, climate, topography, and lithology are some of the natural influences on water quality (Uddin et al., 2018). On the other hands, anthropogenic activities like mining, livestock rearing, waste generation and disposal (industrial, municipal, and agricultural), altered land use leading to sediment runoff, and heavy metal contamination detrimentally impact water quality (Sánchez et al., 2007). In recent times, however, the challenge of enhancing water supply and sanitation in developing nations has been compounded by the daunting task of safeguarding water quality (Carvalho et al., 2011; Debels et al., 2005; Kiprono, 2017). Even well-developed countries, the United States of America and Canada, still grapple with maintaining or elevating water quality amidst issues such as nutrient enrichment and water resource eutrophication alongside escalating demands for water and wastewater services due to population growth (Gómez & Licursi, 2001). Meanwhile, accurate water quality assessment requires sophisticated equipment that is inaccessible to the general public (Abbasi & Abbasi, 2012). This predicament amplifies the implications of contaminated water on both rural and urban populations, catalyzing disease propagation. The concept of the Water Quality Monitoring System (WQMS) was to develop a simple water quality testing equipment for quicker water quality assessment. Therefore, the determination of the quality of water before usage is paramount, but this is not the case in developing countries, where standard equipment is not only expensive but also not easily accessible. This paper presented the evaluation of a developed Water Quality Monitoring System (WQMS) along with the determination of the water quality status based on 5 studied physicochemical parameters. pH, EC,

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TDS, Turbidity, and temperature alongside water quality status, along with the study of the weighted Arithmetic Water Quality Index (AWQI). The novelty of the WQMS was its integrated approach design, simplicity in application, affordability of the hardware (microcontroller and sensors) and IOT information system that facilitate measured water quality parameters in real time.

2. Water quality testing and the Arithmetic Water Quality Index (AWQI)

The evolution of an advanced water quality testing device emerges as a potential remedy, aiming to transcend these constraints the provision of an enhanced, economical, and user-friendly solution. The establishment of drinking water quality standards serves the dual purpose of safeguarding the integrity of drinking water supplies and upholding public health (Standard Organization of Nigeria, 2007). Effective water quality management necessitates the handling and examination of extensive datasets, often challenging to assess and consolidate (Sánchez et al., 2007; Jha et al., 2015). For effective appraisal of water quality data, there is a need for modeling. One of the most studied and well-reported models for water quality appraisal is the Water Quality Index (WQI), Sun et al. (2016), Kannel et al. (2007), Sutadian et al. (2016), Das and Das (2023, 2024), Das et al. (2023). WQI models hinge on aggregation functions, enabling the scrutiny of extensive, temporally and spatially variant water quality datasets to yield a singular metric: the water quality index, denoting the overall water body quality. They transformed intricate water quality datasets into a comprehensible single-value metric of water quality (Bowie et al., 1985; Vallet et al., 2014; Shah, 2017; Spellman, 2013, 2017). The existing water quality monitoring system requires samples to be taken to the laboratory for examination. This test's results, though reliable, it is costly, can be time-consuming, and might not be representative due to deterioration in samples because of delay and lack of proper preservation (Tarras-Wahlberg et al., 2003; Davis, 2010, Tchobanoglous et al., 1985; Tchobanoglous & Schroeder, 1985; UNICEF, 2013). There is a need to develop an appropriate multiple water quality parameter testing system for water quality monitoring in developing countries.

3. Methodology

3.1. The Development of the Water Quality Monitoring System (WQMS)

3.1.1. The study area

This study involved the fabrication, assembly, and testing of a Water Quality Monitoring System (WQMS) through standard procedures described in Atojunere and Ogedengbe (2019), Atojunere et al. (2010), Atojunere (2021, 2026), and Atojunere and Amiegbe (2024), Atojunere and Omotoro (2024). The Water Quality Status (WQS) was calculated using the Arithmetic Water Quality Index (Brown et al., 1972; Krishnan et al., 1995). Published works by Alley (2007), Bozorg-Haddad et al. (2017), Centre for Affordable Water and Sanitation Technology (2013), Chatterjee (2001), Davis and Masten (2004), Atojunere and Ogedengbe (2018), Atojunere and Ogundipe (2022), Fashanu et al. (2019), Eijkelkamp Agrisearch Equipment (2021), El-Shafeiy et al. (2023), Edzwald (2010), Gómez and Licursi (2001), Gray (2008, 2010) were thoroughly reviewed as guides for the water quality assessment section of this study.

3.1.2. Water sampling procedure, collection, and testing

The study was carried out in Lagos and Ogun States of Nigeria, on coordinates 6.5244° N, 3.3792° E and 6.9980° N, 3.4737° E, with populations of 16 million and 8 million (National Population Commission, 2006), respectively. Five sampling points, S_1–S_5, were selected for this study at the entry and exit of the River Ogun in Lagos due to its importance for domestic, industrial, and recreational usage. They were S_1 River Ogun (RO), S_2 well water (WW), S_3 Rainwater (RW), S_4 Neimeth Wastewater (NW), and S_5 Sea water Eleko beach (SW), respectively, as shown in Figure 1.

3.1.3. Water sampling procedure, collection, and testing

Five 5 physicochemical parameters, pH, temperature, Electrical conductivity (EC), Total Dissolved Solids (TDS), and turbidity, were measured with WQMS and METCOM Bluelab Combo Meter (MBCM), both in situ and in the laboratory. This was done by inserting each of the WQMS's sensor probes of turbidity, pH, EC, TDS, and temperature into the water bodies facing upstream. Water samples were collected at sampling sites S_1–S_5 for laboratory tests in clean Polyethylene Terephthalate (PET) bottles. The trapping of air bubbles and contamination were avoided during sampling at River Ogun and the Eleko beach by immersing the PET sample bottles facing the water current (American Public Health Association, 2021; Bain et al., 2012).

3.2. The operation of WQMS

The WQMS consisted of an electronic casing with a backlit Light Emitting Diode (LED) screen that housed the system's performing circuits, an Arduino Nano microprocessor, and detachable probes of 5 water quality sensors- pH, temperature, EC, TDS, and turbidity. WQMS has a switch button, and the system was powered by a 5-Volt rechargeable battery, as shown in Figure 2. The fabrication and assembly of WQMS's component, writing of codes, calibration of the sensors, and testing followed standard procedures. Key steps included in the calibration were preparing the sensors with each sensor's calibration solutions or standards, taking readings, and making necessary adjustments. The materials utilized for the construction of WQMS are listed in Table 1. The sensors' shroud was attached to the WQMS electrical sockets for measuring multiple water

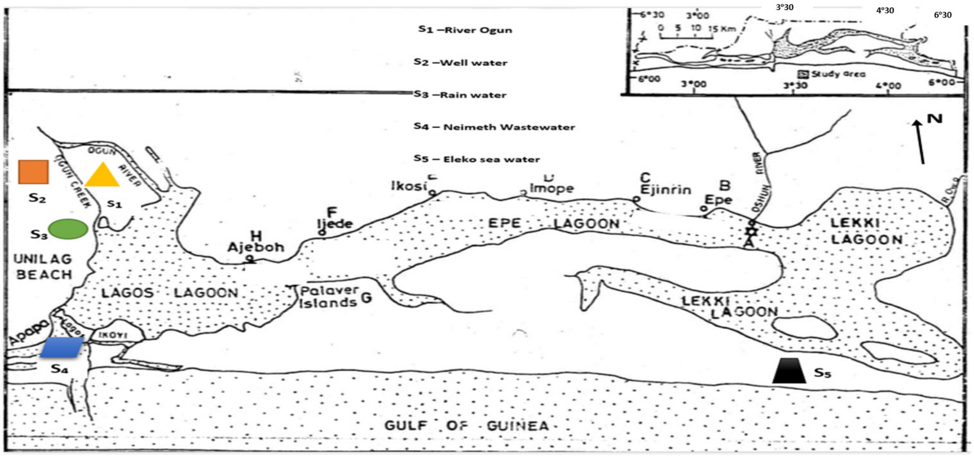

Figure 1. Map of lagos, showing sampling and testing sites for WQMS and MCBM (Uwadiae, 2010, with modification)

quality parameters of water in a single attempt. However, in the laboratory, the sensor probes were inserted into a sample of water taken from selected points placed inside a 250-Erlenmeyer flask, and readings were taken through the backlit (LED) screen within 2–5 seconds. WQMS was suitable for field and laboratory purposes. The MBCM, a calibrated reference system, served as a control and was used to measure the same 5 parameters, pH, conductivity, turbidity, temperature, and TDS, on the water samples tested by WQMS. Unlike WQMS, MBCM was very expensive and often used in the laboratory. Statistical analysis and the weighted arithmetic water quality index (WQI) were carried out on physico-chemical parameters data obtained from MBCM and WQMS.

3.3. Different water quality index versus the weighted Arithmetic Water Quality Index (AWQI)

Different Water Quality Indexes (WQI) employed a distinct number of parameters to estimate WQI. While the Canadian Council of Ministers of the Environment (CCME) Water Quality Index utilized a range of water quality indicators based on the specific application, the National Sanitation Foundation (NSF) WQI used 9 parameters for estimation. However, others may utilize up to 20 parameters or more, and the weighted Arithmetic Water Quality Index (WQI) models for this study used 5 parameters (Table 2).

Table 1. The materials for the construction of WQMS

S/N	Items	Quantity	Purpose
1	Arduino ESP32	1	Communicates with sensors and controls.
2	pH sensor	1	It measures the pH values of samples.
3	EC sensor	1	It measures the EC values of samples.
4	Temperature sensor: DS18B20	1	It measures the temperature values of samples within the range of –55 °C to +125 °C.
5	Total dissolved solids (TDS) sensor	1	It measures the TDS values of samples.
6	Sensor for turbidity:	1	It measures the turbidity values of samples.
7	Display unit: LED display	1	The display received a signal in a human-readable digital format.
8	Power source: Lion-ion battery with buck-boost converter.	1	Constitutes a rechargeable energy storage solution that harnesses lithium ions to accumulate and discharge electrical energy.
9	Wiring and connectors: jumper wires, connectors, and cables	1 packet	To connect the components to the ESP32 board.
10	Calibration solutions	5	Helps to achieve the accuracy that's critical for measuring pH, TDS, EC, Turbidity, and Temperature in water samples.
11	Bluetooth module	1	An interface to communicate with smartphones or computers wirelessly.
12	Resistors and capacitors:	2	Passive components for sensor interfacing and noise reduction.
14	Conical flasks, PET bottles, funnel	5	for water sampling.
15	METCOM Bluelab Combo Meter	1	It combines multiple measurement functions into a single instrument. It was used as a calibrated system.
16	Tolsen soldering iron 60 W	1	To join the work piece.
17	Solder wire, Tolsen screwdrivers, and Tolsen pliers	1 coil,6 sets,1	For joining components and drawing in nails during assembly.

Table 2. Benefits and limitations of the Arithmetic Water Quality Index method

1	Incorporate data from multiple water quality parameters into a mathematical equation that rates the health of a water body with numbers.	WQI may not carry enough information about the real quality situation of the water.
2	Less number of parameters are required in comparison to all the water quality parameters required for a particular use.	Many uses of the water quality data cannot be met with an index.
3	Useful for the communication of overall water quality information to the concerned citizens and policymakers.	The eclipsing or over-emphasizing of a single bad parameter value.
4	Reflects the composite influence of different parameters, importance for the assessment and management of water quality.	A single number cannot tell the whole story of water quality. There are many other water quality parameters that are not included in the index.
5	Describe the suitability of both surface and groundwater sources for human consumption.	WQI, based on some vital parameters, can provide a simple indicator of water quality.

Table 3. Standard limit for water quality parameters (NSDWQ) / WHO 2017; BIS, 2012)

S/N	Parameter	Standard value (V_S) (NSDWQ)	WHO (2017)	BIS (2012)	Ideal value (V_i)
1	pH	6.5–8	6.5–8	6.5–8.5	7
2	Temperature	25	28	–	0
3	TDS	500	500	500	0
4	Turbidity	5	5	1	0
5	EC	1000	250	–	0

The WQI calculation was conducted through the application of a weighted arithmetic index method, as outlined by Brown et al. (1972), DeZuane (1997), Hsu and Sandford (2007), Sun et al. (2016), Zhang et al. (2010), Das (2022, 2024, 2025a, 2025b). It was computed utilizing the drinking water quality standards from the World Health Organization (WHO), National Standard for Drinking Water Quality (NSDWQ), the Bureau of Indian Standards [BIS] (2012), and the Indian Council for Medical Research [ICMR] (1975). The weighted arithmetic index method aggregated multiple water quality parameters into a single value that represents the overall quality of the water as expressed in Eqs. 1–3. The unit weight (w_n) values were calculated based on a suggestion from Krishnan et al. (1995). The WQI models consisted of 4 consecutive phases: (1) the selection of pertinent water quality parameters, (2) the generation of sub-indices corresponding to each parameter, (3) the calculation of weighting values for the parameters, and (4) the aggregation of sub-indices to derive the comprehensive water quality index. Based on previous studies, each parameter was ranked based on its importance in the following order: pH, turbidity, EC, TDS, and Temperature. Parameters such as pH and turbidity received a higher rank due to their greater impact and were assigned to a higher weight based on water quality and human health implications. This is followed by other parameters such as EC, TDS, and temperature, while DO and BOD were important parameters; however, they were not measured by WQMS.

$$WQI = \frac{W_1 \times I_1 + W_2 \times I_2 + \cdots + W_n \times I_n}{W_1 + W_2 + \cdots + W_n}, \tag{1}$$

W_i = Weight assigned to the ith water quality parameter. I_i = Sub-index value for the ith parameter, obtained from the parameter's measurement and a corresponding standard. *WQI* was calculated with the arithmetic index method in the following steps:

I_i values are given by the relationship below in Eq. (2);

$$I_i = 100\left(V_n - V_i\right) / \left(V_s - V_i\right), \tag{2}$$

V_s = standard value, V_n = Observed value, V_i = ideal value.

Except for pH (ideal value is 7, all other parameters' ideal values were 0 as shown in Table 3.

Eq. (3) presented (W_n), which is inversely proportional to the recommended standards for the corresponding parameters.

$$W_n = K / S_n, \tag{3}$$

W_n = Weight assigned to the nth water quality parameter; S_n = Standard permissible for nth quality parameters; K = Proportionality constant.

Each parameter's quality rating scale (Q_i) was calculated as follows (Eq. (4)).

$$Q_i = \left(\frac{V_n - V_i}{V_s - V_i}\right). \tag{4}$$

For the pH, the quality rating was calculated as (Eq. 5)

$$QpH = \left(\frac{V_i - 7}{V_s - 7}\right). \tag{5}$$

3.4. Computation, statistical analysis

The relationship among the studied parameters was determined using inferential statistics such as Spearman's rho (ρ) correlation analysis, and Analysis of Variance (ANOVA) was carried out on the data obtained from the physicochemical test.

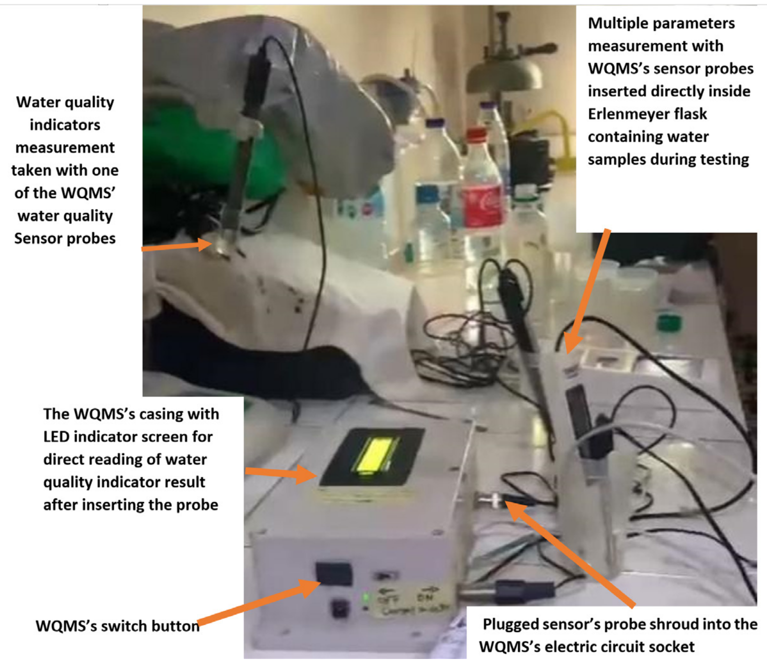

Figure 2. The WQMS under loading conditions for pH, EC, TDS, turbidity, and temperature measurement

4. Results of the research

The results of the physicochemical tests point S_1–S_5 for pH, Temperature, EC, TDS, and Turbidity obtained from WQMS and the MBCM were presented in Table 4 whereas Table 5 contained their corresponding calculated water quality indexes.

Table 4. Physicochemical parameters from WQMS and MBCM and Water Quality Index Status Report on water samples tested

Tested water samples	Type of test	Temperature	pH	EC (μS/cm)	TDS	Turbidity
Well water, (S_2) WW	Standard method	28.25	5.79–5.91	604.5–610.1	165	< 5
	WQMS	28.25	5	650	161.45	< 5
Sea water, (S_5) SW	Standard method	28.12	6.76–7.04	6233–12243	519	< 15
	WQMS	28.12	5.96	5097–12884	515.7	< 15
Neimeth waste water (S_4)-NW	Standard method	28.44	7.76	469–471.9	85	< 12
	WQMS	28.44	7.76	464.13	70.92	< 10
Rain water, (S_3) RW	Standard method	28	5.76	32.24–34.39	4	< 8
	WQMS	28	5.74	33.97	5.76	8
River water, (S_1) RO	Standard method	28.25	6.18–6.28	1240–1273	223–227	< 5
	WQMS	28.25	6.22–6.13	1272–1280	248.33	< 5

Table 5. Water Quality Status (WQS) based on studied parameter with water quality referenced guidelines

Parameters	Standard	S_n	W_n	S_2	S_5	S_4	S_3	S_1
Temp. °C	NSDWQ (2007)	25	0.1	28.9	28.8	29	28.8	28.8
pH	WHO (2017)	8.5	0.2	5.9	7.2	7.4	6.2	6.2
EC μS/cm	ICMR (1975)	300	0.002	478	11990	311	672	672
TDS ppm	ICMR (1975)	500	0.001	239	5996	155	336	336
Turbidity NTU	BIS (2012)	10	0.01	0.9	1	0.9	1	5
WQI				34.59	30	14.79	24.32	23.39
WQS				Good water quality	Good water quality	Excellent water quality	Good water quality	Good water

5. Discussion and interpretation of results obtained

5.1. Water quality parameters results

The result indicated that all the studied water quality indicators of WQMS and MBCM were significantly different. These values demonstrated the reliability of WQMS with an accuracy of 78% to measure multiple water quality indicators at a single attempt and its alignment with the reference standard for the permissible limit. The referenced guidelines for water quality are shown in Table 6. The results support the appropriateness of WQMS as an appropriate water testing technology for developing countries, with affordable cost, flexibility, adjustable for hard-to-reach sampling points, and user-friendly.

5.2. Water quality parameters interpretation

From Tables 4–5, it was observed that there were variations among the studied parameters, as shown in Figures 3–6. This might be attributed to the fact that the WQMS sensor system was generating accurate data at different water conditions. The chances of obtaining significantly different measurements for the same condition were minimized, and any observed changes are more likely due to real variations rather than random fluctuations. The importance of these measured water quality parameters in determining the overall water quality was discussed below.

First, the pH is an important parameter because it points out the acidity or alkalinity of the water. If it is less, algae die, fish cannot reproduce, and it causes acidity, corrosion, irritation of mucous membranes, tuberculosis, and other health problems in humans. Electrical conductivity is another important parameter for determining the water quality for drinking and agricultural purposes. Second, the TDS, EC, and temperature were useful parameters to establish the overall water quality and suitability for various purposes. Third, turbidity is used to determine water clarity, indicating the presence of suspended particles, including harmful microorganisms. If the Total dissolved solids TDS is more, water cannot be used for drinking or construction purposes. TDS affects the palatability of food cooked and also causes gastrointestinal irritation. The high TDS in the Ogun River may indicate that pollution is building up upstream from runoff or industrial discharge. Lastly, the importance of temperature cannot be overemphasized; temperature affects the solubility of gases, chemical reaction rates, and the survival of aquatic organisms, as well as the Dissolved Oxygen (DO) levels present in the water.

There was variation in the efficiency of WQMS and MCMB based on the physico-chemical parameters studied. While WQMS was 78 % while MCMB is 82 % (Table 6) respectively. This finding is not surprising because WQMS needs longer water quality measurement and the MCMB is already an established water quality testing device. The finding indicated that the WQMS is potent to determine the quality of several water sources based on the 5 physio-chemical parameters studied with their WQS determined.

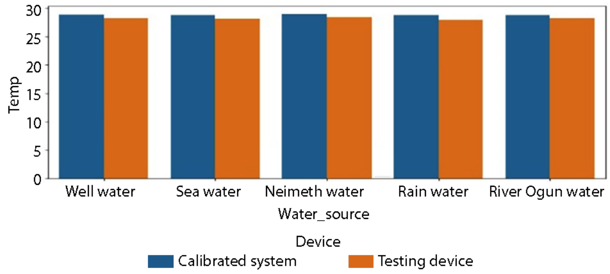

Figure 3. The bar chart of water temperature values from WQMS and MBCM at sites S_1–S_5

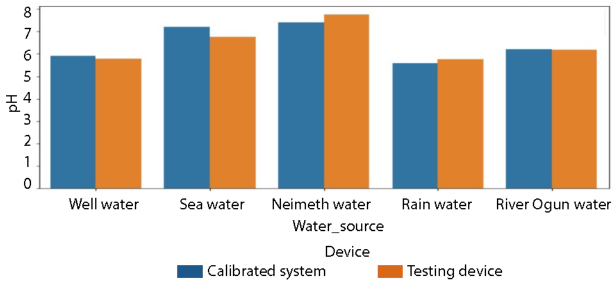

Figure 4. The bar chart of the pH values from WQMS and MBCM at sites S_1–S_5

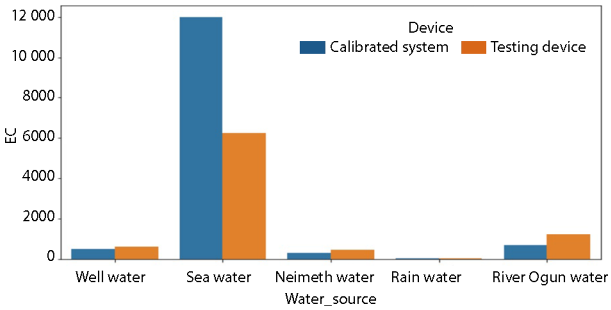

Figure 5. The bar chart of EC values from WQMS and MBCM at sites, S_1–S_5

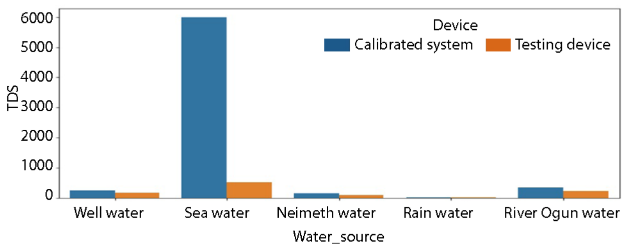

Figure 6. Bar chart of TDS values from WQMS and MBCM at different sites, S_1–S_5

Table 6. Comparison of WQMS and the Control meter based on the Studied physico-chemical parameters

S/N	Current study WQMS	Previous study (control meter)
Efficiency %	78	82

5.3. Comparison of results with WHO and NSDWQ Standards

The observed values (Table 4) aligned with the WHO and the Nigerian Standard for Drinking Water Quality (NSDWQ) on water quality for all studied parameters. However, higher TDS values raised a flag which might not be unconnected to contamination from anthropogenic and natural sources.

5.4. Water Quality Index (WQI) Interpretation

The Water Quality Status (WQS) results presented in Table 5, according to Chatterjee and Raziuddin (2002) in Table 6, suggested that all were within the good-excellent water range of grading B for S_1, S_2, S_3, S_4, and S_5, respectively. The Water Quality Indicator (WQI)-Light green and blue colours were the acceptable limit, while others, yellow, red, and black, were not, as shown in Table 7.

Table 7. Water Quality rating as per the weight Arithmetic Water Quality Index method (Chatterjee & Raziuddin, 2002)

WQI value	Rating of Water Quality	Grading	
0–25	Excellent water quality	A	
26–50	Good water quality	B	
51–75	Poor water quality	C	
76–100	Very poor water quality	D	
Above 100	Unsuitable for drinking purposes	E	

5.5. Statistical analysis and correlation

Statistical data showed that there was a strong correlation coefficient $\rho of 1$ between the MBCM-calibrated System and the WQMS readings for EC, pH, and TDS. The WQI results on 5 studied water quality indicators showed similarity with other work (Singh et al., 2015; Ram et al., 2021; Lakshmikantha et al., 2021). While some water quality parameters had strong positive and perfect relationships, and the measurements obtained from both systems closely follow each other, the correlation coefficient of temperature data was 0.75. This could mean that a strong positive linear relationship among the water quality indicators measured by WQMS. The trend was that the measurements from the MBCM and WQMS exhibited both degrees of similarity and variability or deviation. However, the standard deviation σ measurements from the EC and TDS sensor system revealed that the values were scattered and exhibited greater variability around the mean (average) values.

5.6. Limitations and challenges

Some measured parameters showed inconsistency and were scattered. This might not be unconnected to the calibration of the sensors in this work, and by extension, malfunction of the sensors may arise. Calibration errors, noise, or environmental factors may contribute to the observed variability in parameters recorded by WQMS. The following steps were carried out to minimize these challenges: assessment of sensor accuracy, rechecking of calibration methods, environmental factors, and physical properties of the system. More so, the Arithmetic WQI was tailored to specific regional guidelines, rendering them less universally applicable. It introduced uncertainty when transforming substantial water quality datasets into a singular index value (Uddin et al., 2018). In a hard-to-reach sampling point, the testing was done by abstracting water from selected points with Erlenmeyer flasks, followed by inserting the sensor probes to take measurements. This is to prevent WQMS from damage due to the short length of the cable (2 metres) and the sensor probes.

6. Conclusions

This study demonstrated the capacity of the developed WQMS to determine multiple water quality indicators in a single attempt. It is an appropriate technology, fast and affordable, with an accuracy of 78 %. 5 studied parameters measured by WQMS and the MBCM (control) temperature, and pH, EC, TDS, and turbidity were significantly different, which might be attributed to different calibrations and system performance of the devices. The threshold of the calculated Arithmetic Water Quality Index (WQI) for well water, rainwater, Neimeth water, and River Ogun was below the WQI threshold of 25, while seawater has a WQI of 26 to 50. The water quality status indicated that the quality of the water samples was good. The statistical result further shows that a low standard deviation existed between pH and temperature values at Alpha 0.05, and variability was recorded between EC and TDS values, probably due to the buildup of pollution upstream due to anthropogenic and natural activities along the water course. Further study is required to perfect the working principles of WQMS and make it more reliable.

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Conflict of interest

The authors declared that there was no conflict of interest.

Authors' contribution

Conceptualization, A.E.E., methodology, A.E.E and G.A.O.; software, G.A.O.; validation A.E.E. and G.A.O.; and; formal analysis, A.E.E. and G.A.O.; investigation, A.E.E. and G.A.O.; resources A.E.E. and G.A.O.; data curation, A.E.E. and G.A.O.; writing – original draft preparation, A.E.E, writing – review and editing visualization, A.E.E. supervision, A.E.E and project administration, A.E.E. The authors have read and agreed to the published version of the manuscript.

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