LAUTECH Journal of Engineering and Technology 18 (3) 2024: 21-30
10.36108/laujet/4202.81.0330

Evaluating water quality dynamics: a strategic tool for optimizing water treatment operations

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Article Info

Article history:

Received: March 5, 2024
Revised: Sept 2, 2024
Accepted: Sept 4, 2024

Keywords:

Water quality,
Water treatment,
Water quality index,
Treatment system

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ABSTRACT

Water quality and treatment systems are dynamic because they constantly undergo seasonal variations in water chemistry, varying plant operating conditions, and new environmental laws, among others. Because of this, proper monitoring is essential to ensure that the water supplied by the treatment system safeguards public health from waterborne diseases. Selected surface water quality parameters as inflow were obtained before treatment against the treated water for different hydrological periods (2009 – 2019) from a water treatment system to determine the trend in water quality variation, water quality index and effectiveness of the treatment process. Each hydrologic year had varying concentrations of selected parameters for raw and treated water quality. The concentration values of pH, electrical conductivity, total hardness, calcium and magnesium hardness, chloride, and total dissolved solids of the natural source water were within the recommended limit. Turbidity concentrations were above the recommended value for each hydrologic year, values ranging from 14.65 – 57.98 NTU and iron concentration was above the permissible for 2010 and 2012. Selected parameters were all within the threshold limit after treatment, water quality index (WQI) ranged between 1.09 – 39.39 which is rated as good/excellent water quality. The treatment system operations were effective throughout the observation period. However, turbidity, iron and hardness should be tested more frequently as part of the operational and verification monitoring process.

INTRODUCTION

The increasing vulnerability of water resources is one of the great challenges to humanity in recent times (Brkic *et al.* 2019, Stehle & Schulz (2015). Water quality issues are of great concern now more than ever because of the rapid urbanization and population explosion. Water makes up about 50–97% of the weight of all plants and animals, yet it is the most poorly managed resource in the world. The quality of surface water is constantly changing in response to daily, seasonal, and climatic conditions because it depends on the equilibrium between the physical, chemical, and biological characteristics of the surrounding environment. Hence, the proportion of available but polluted water is continuously increasing as a result of changes in the modes of industrial activities, agricultural production, runoffs, and increasing urbanization which results in diarrhoea, cholera, dysentery, and various other diseases like typhoid, amoebiasis, jaundice, enterobacteriaceae, etc when consumed and many infectious diseases are transmitted by water through the fecal-oral route. It was reported that approximately 36% of urban and 65% of rural Nigeria lack access to safe drinking water (USAID, 2010). Excellent water quality resources are of great influence in maintaining healthy living and sustainable socio-economic development in a community (Sin & Lee, 2020).

Regular water quality assessment is essential for surface water management. This reduces risks associated with chemical underfeeding or overfeeding in treatment plants, assists in maintaining continuing compliance with environmental regulations, improves the quality of plant operation, increases water and energy savings, and improves plant productivity. Water treatment systems can be monitored by manual methods or by continuous systems employing automatic instrumentation. The former is economical in the developing world since it typically involves plant operators or technicians conducting chemical tests and comparing the results to specified chemical control limits. The testing frequency can vary from once per hour to once per day or year, depending on the resources available while the automatic instrumentation requires improved reliability and quality, and a higher degree of precision is required since results are recorded automatically.

Studies have been carried out on the variation of water quality (Seif *et al.* 2020, Olaoye *et al*. 2021, Simoes *et al*., 2008); due to significant concentration of pollutants from industrial effluent discharge into the water (Yan *et al*. 2022, Olaoye *et al.* 2018). However, regular water quality monitoring is rarely carried out in most surface water in developing countries, which is expected to serve as a pollution control measure and management strategy to various degrees of anthropogenic activities carried out in and around the water source most especially, land use pattern induced by the use of fertilizers and dumping of industrial, domestic and agricultural wastes.

In this study, selected water quality parameters from surface water resources were obtained against the treated water between 2009-2019 from Ogun State water supply treatment scheme to determine the trend in water quality variation, the water quality index and the effectiveness of the treatment system as a tool for water quality management, pollution control and enforcement of water resources regulations.

METHODOLOGY

Study Area

The land use structure of the study area (Ogun State, Southwestern, Nigeria) is categorized into six. Based primarily on types of land use, consideration for human activities, sewage and effluents flowing from industries. These are;

i. Administrative Division: Reserved area for official activities
ii. Human Settlements: Mowe, Ibafo, Ojodu, Akute, Ota, Itele and Ifo human settlements are growing significantly and are expected to absorb more population, in addition to these, pressure from Lagos State interurban settlement continues to be the dominant factor in the State urban settlement.
iii. Economic: Industrial areas; Ota and Agbara Industrial Estates and others for tourism
iv. Infrastructures: Lands acquired by Government for dams, highways, and air and sea ports
v. Institutional: land acquired for social uses such as schools, hospitals, military and similar uses
vi. Protected Ecological Zones and Green Belts: Agricultural activities

Water demand was estimated to be 50 litres per capita per day and 150 liters per capita per day for rural and urban centers respectively (OGSWC, 2010)

Data collection

Surface water quality data as inflow were obtained before treatment against the treated water between different hydrological periods 2009 – 2019 from the

Ogun State water treatment scheme to determine the trend in water quality variation, water quality index (rating values given in Table 1) and effectiveness of the treatment system. Selected water parameters observed were pH, conductivity in µS/cm, turbidity in NTU, total hardness (mg/L), calcium hardness and magnesium hardness (mg/L), chloride (mg/L), iron (mg/L) and total dissolved solids (mg/L).

The quality rating scale Q_n for each parameter was calculated using equation 1;

$$Q_n = 100 \times \frac{V_n - V_o}{S_n - V_o} \quad (1)$$

Where

Q_n = Quality rating for the nth water quality parameter;
V_n = Estimated concentration of n^{th} parameters in the water samples;
V_o = Ideal value level of the analysed parameters in pure water;
S_n = Recommended data value n^{th} parameters
The unit weight W_n for each water quality parameter was calculated using Equation 2;

$$W_n = \frac{K}{S_n} \quad (2)$$

Where

W_n = Unit weight for the n^{th} parameter;
S_n = Recommended data value n^{th} parameters;
K = Proportionality constant`

$$K = \left(\frac{1}{\sum Sn}\right)^{-1}$$

The water quality index (WQI) was calculated using the weighted arithmetic method as given in equation 3 (Eqn.3);

$$\text{Water Quality Index} = \frac{\sum W_n Q_n}{\sum W_n} \quad (3)$$

RESULTS AND DISCUSSION

Variation of Physicochemical Parameters

The variation of physicochemical properties of the water parameters for both raw and treated water samples are shown in Tables 2 and 3, respectively. The descriptive statistics show that most of the parameters of the treated water samples had lower standard deviations compared to the raw water. The average annual pH value between 2009 – 2019 of water inflow into the treatment system was slightly above neutral to alkaline, ranging between 7.18 – 8.0 while the pH value for the treated water was slightly acidic (from 6.68) to neutral with a pH of 7.33 (Fig.1a).

Where;

W_n = Unit weight for each water quality parameter
Q_n = Quality rating scale for each parameter
The water quality classification standard shown in Table 1 was used to evaluate the classification of each index in the hydrological periods.

Table 1: Water Quality Rating (WAWQI)

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

Source: Tyagi *et al*. (2013)

Statistical analysis

Statistical analysis was performed using Statistical Package for Social Sciences (SPSS). The Principal Component Analysis (PCA) was used to determine the interrelationships among the water quality variables and also to identify the parameters that require constant checking and monitoring.

Table 2: Descriptive Statistics of the Raw Water

	Minimum	Maximum	Mean	Std. Deviation
pH	7.18	7.99	7.425	0.294
Conductivity *(µS/cm)*	122.93	299.88	179.923	68.961
Turbidity *(NTU)*	14.65	57.98	37.876	14.736
TH *(mg/l)*	16.02	62.32	43.435	12.170
Ca.H *(mg/l)*	11.56	37.53	27.110	6.590
Mg.H *(mg/l)*	4.46	26.60	16.978	7.121
Chloride *(mg/l)*	13.71	36.60	31.011	6.517
Iron *(mg/l)*	0.10	0.92	0.275	0.232
TDS *(mg/l)*	22.52	77.25	52.232	17.947

pH Value: The concentrations of hydrogen ions, pH, were within the recommended WHO value of 6.5 – 8.5. A similar value below the permissible was reported by Akongyuure and Alhassan (2021) from the Tono reservoir.

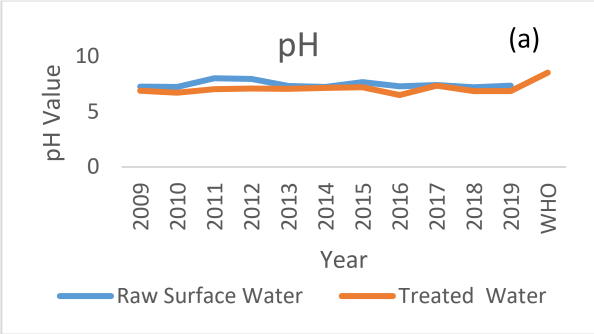
Table 3: Descriptive Statistics of the Treated Water

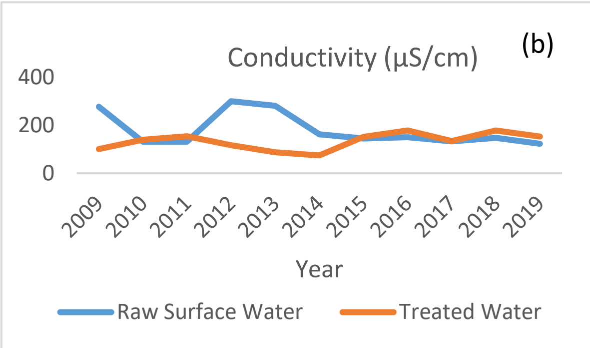
	Minimum	Maximum	Mean	Std. Deviation
pH	6.48	7.33	6.947	0.241
Conductivity *(µS/cm)*	74.46	178.31	133.683	34.749
Turbidity *(NTU)*	0.64	3.50	1.710	0.797
TH *(mg/l)*	17.80	68.67	47.014	13.724
Ca.H *(mg/l)*	14.40	45.41	31.190	6.239
Mg.H *(mg/l)*	3.40	25.85	18.001	7.454
Chloride *(mg/l)*	15.85	53.08	36.215	6.833
Iron *(mg/l)*	0.00	0.06	.0173	0.026
TDS *(mg/l)*	34.71	76.65	61.490	16.073

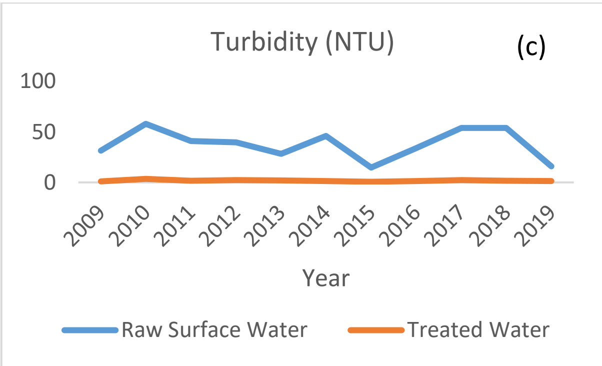
Electrical conductivity (EC): Average electrical conductivity (EC) of inflow and treated water ranged from 131.38 –299.88 µS/cm and 74.46 – 178.31 µS/cm respectively (Fig.1b), these were within the normal values often found in surface and treated water. Arimieari *et al*.2014 and Awomeso *et al*. 2019 reported higher but similar results from three and eight water basins in Port Harcourt and Ogun State respectively. These values indicated that the water source has little interference from dissolved minerals and salts Akongyuure and Alhassan 2021.

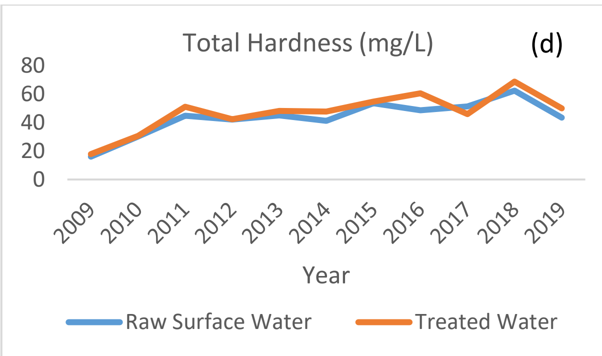
Turbidity: High levels of turbidity value were recorded throughout the observation period of 11 years at the inflow. Values range from 14.65 – 57.98 NTU (Fig.1c). Indicating very low water quality due to high pollution load from anthropogenic activities in the study area. High turbidity values often protect microorganisms and pathogens from the effects of disinfection, stimulate the growth of bacteria and give rise to significant chlorine demand during treatment. Sporadic high turbidity in source water can interfere with and overwhelm treatment processes, allowing enteric pathogens into treated water and the distribution system. High turbidity values were also recorded at the upstream of Ethiopian River by Fikadu (2022) due to land use patterns and urbanization. The turbidity of the treated water ranged from 0.64 – 3.5 NTU. The lowest value of 0.64NTU was observed in 2015 while 3.5 NTU was observed in 2010.

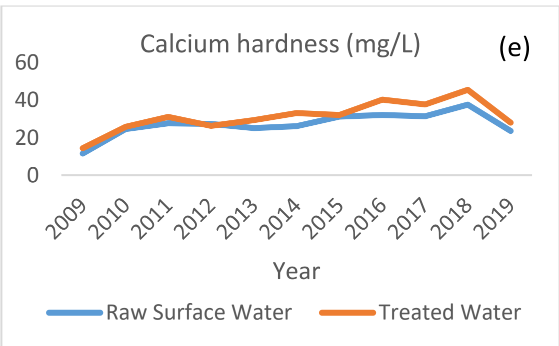
Total hardness: The total hardness value of the source water between 2009 and 2019 was between16.06 – 62.32 mg/L while the treated water ranged between 17.8 – 68.67mg/L indicating soft to moderately hard water (Fig.1d). Values were within the recommended standard. Hardness in water is caused by a variety of dissolved polyvalent metallic ions, predominantly calcium and magnesium cations. It is usually expressed as milligrams of calcium carbonate per litre. Hardness is the measure of the capacity of water to react with soap, hard water requires considerably more soap to produce a lather. The degree of hardness of drinking water is important for aesthetic acceptability by consumers because water with high hardness will produce a cloudy appearance. Public acceptability of the degree of hardness of water may vary considerably from one community to another.

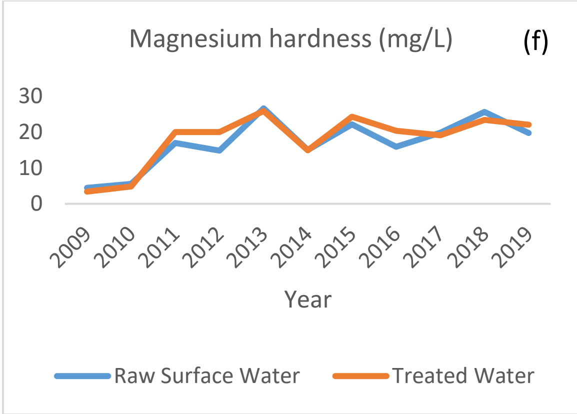


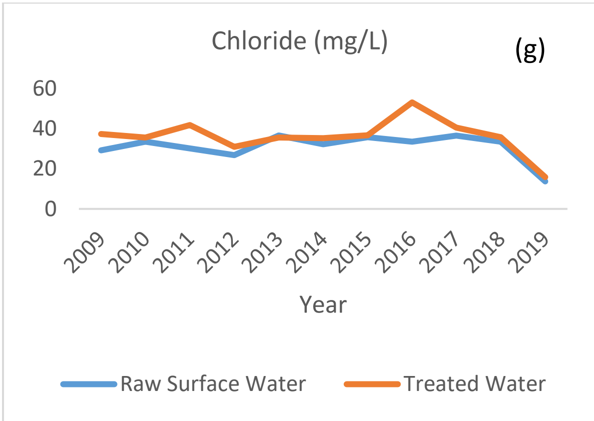


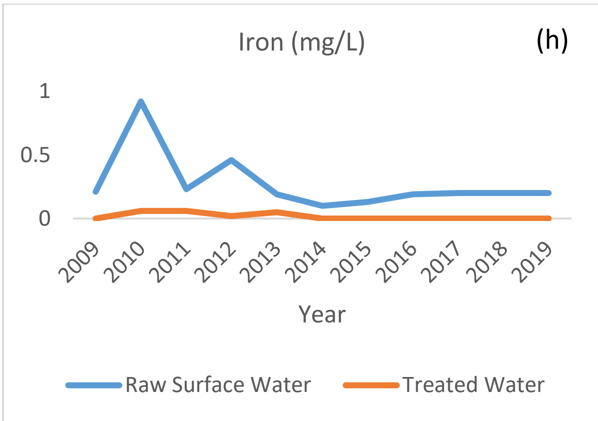












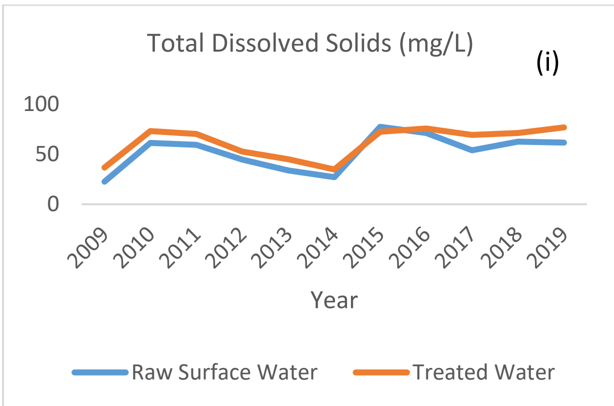


Figure 1 (a)- (i): Variation of water quality

Calcium and magnesium hardness: Concentration of calcium and magnesium hardness in the source water varied between 11.56 –37.53 mg/L and 4.46 – 25.64mg/L respectively, Fig. 1(e) & (f). This shows that the concentration of calcium hardness was found to be higher than that of magnesium hardness, similarly reported by Fikadu (2022). The treated water had a calcium concentration value between 14.4 – 45.41mg/L while the treated water had magnesium hardness between 3.4 – 25.85mg/L. Both calcium and magnesium are essential minerals and beneficial to human health in several respects. Inadequate intake of either nutrient can result in adverse health consequences.

Chloride: Chloride ion concentration in the source water between 2009 - 2019 ranged from 13.71 –36.6 mg/L while in the treated water concentration ranged from 15.85 –53.08mg/L (Fig.1g). Obtained values were below the recommended 250mg/L. Similarly, in a US geographical survey conducted to determine the chloride concentration in 95 surface water resources dominated by forest, agriculture, and urban land settlement between 1991 -2003, results indicated that chloride levels were in the range of 21, 44, and 30mg/L respectively (Mullaney *et al*., 2009). The iron concentration of the water source ranged between 0.1 – 0.92mg/L while the treated water had an iron concentration between 0 – 0.06mg/L (Fig.1h).

Iron: Iron in the water source is indicative of agricultural activities (drainage/irrigation). Higher concentrations of iron in three surface waters in Port Harcourt, Nigeria were reported by Arimieari *et al*. 2014 with values between 0.176 to 0.866mg/L. However, the iron concentrations were within the permissible threshold of 0.3mg/L recommended by WHO.

Total Dissolved Solids: The concentration of TDS in the water source was between 22.52 – 77.25mg/L while the treated was between 36.58 – 76.65mg/L (Fig. 1i). Values obtained were within the recommended WHO value of 300mg/L. A high concentration of TDS (4095 – 19460mg/L) was reported by Arimieari *et al*. (2014) from three surface water bodies. High TDS concentration is indicative of chemical contaminants either organic or inorganic from sewage, water treatment chemicals, agricultural runoff or industrial wastewater.

Water Quality Index

The WQI and water quality rating scales are shown in Table 4. The WQI for the raw water samples characterized ranged between 56.94 – 501.63, rated as poor (C), very poor (D) and unsuitable (E) water for drinking. The WQI for the treated water samples ranged between 1.09 – 22.65, rated as excellent quality (A) and in 2012 WQI obtained was 39.39 rated as good water quality (B), indicating that treated water is suitable for consumption, similar results obtained by Yan *et al*. (2022), Excellent water quality resources are of great influence in maintaining healthy living and sustainable socio-economic development in a community (Sin & Lee, 2020) and tool for checking the effectiveness of water treatment systems.

Correlation Between Physio-Chemical Parameters

The correlation matrix of the physio-chemical parameters of the raw and treated water is shown in Table 5. The dominant parameters of the data set were used for correlation. There was a strong positive and negative correlation among various physicochemical parameters. There was a strong positive linear relationship between calcium hardness and total hardness (0.9) and between magnesium hardness and total hardness (0.8). A strong correlation also exists between iron and turbidity (0.7). This was also revealed in the water characterization. Significant and moderate linear relationship can be seen between magnesium hardness and calcium hardness (0.6), total dissolved solids and total hardness (0.6), total dissolved solids and calcium hardness (0.6) and turbidity and PH (0.5). The interlinkage among other water parameters indicates that the correlation is low or weak, either in a positive or negative direction ranging between 0.1 – 0.4 as shown in Table 5. Geo et al. 2023 and Lopez and Martínez, (2024) also obtained similar statistical results when assessing the efficiency of a coagulation system and the performance of a water treatment plant respectively.

Principal Component Analysis (PCA)

The scree plot spectrum of the water parameters is shown in Figure 2. The plot revealed that only three components have Eigenvalues greater than 1 and are significant since the higher the Eigenvalue the more variance the components. The PCA in Table 6 shows the total variance of the parameters and the three-factor components with Eigenvalues greater than. The Eigenvalue for component one was 3.51 (variance = 38.97%), component two Eigenvalue was 1.96 (variance = 21.82%) and component three Eigenvalue was 1.04 (variance = 11.59%). cumulative variance was 72.37%.

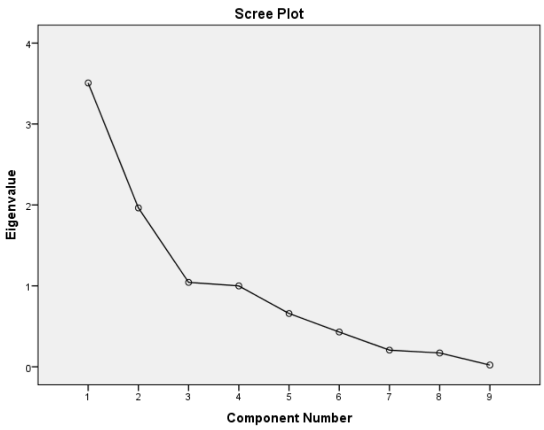


Figure 2: Scree plot spectrum of the data set

The higher the total variance the better as observed in the data set. The remaining six parameters had 27.63% of the total variation. A similar method and results were obtained by Zhou et al. 2023, Zhang et al. 2023, Singh and Singh 2023.

Table 4: WQI and Water Quality Rating for Raw and Treated Water

	Raw water		Treated water	
Year	*WQI*	*Water Quality Rating*	*WQI*	*Water Quality Rating*
2009	97.67	D	1.59	A
2010	338.61	E	20.67	A
2011	115.91	E	20.6	A
2012	183.09	E	39.39	B
2013	88.88	D	18.01	A
2014	501.63	E	22.65	A
2015	56.94	C	1.99	A
2016	94.75	D	1.09	A
2017	119.85	E	4.1	A
2018	119.45	E	2.21	A
2019	78.54	D	1.88	A

CONCLUSION AND RECOMMENDATIONS

Each hydrologic year had varying concentrations of selected raw and treated water quality parameters. The concentration values of pH, electrical conductivity, total hardness, calcium and magnesium hardness, chloride, and total dissolved solids of the natural source water were within the recommended limit. Turbidity concentrations were above the recommended value for each hydrologic year while iron concentration was above the permissible for 2010 and 2012. Selected parameters were all within the threshold limit after treatment with a water quality index (WQI) ranging between 1.09 – 39.39, rated as good/excellent water.

The treatment system operations were effective throughout the observation period. However, turbidity, iron and hardness should be tested more frequently as part of operational and verification monitoring processes. There is a need for routine monitoring of the various anthropogenic or human activities and land use within the study area to bring the source to desirable levels for turbidity and iron.

Table 5: Correlation Matrix of Physio-Chemical Parameters of Water

	pH	EC	Turb.	TH	Ca.H	Mg.H	Cl	Iron	TDS
pH	1								
EC(*µS/cm)*	0.3	1							
Turbidity *(NTU)*	0.5	0.3	1						
TH *(mg/l)*	-0.1	-0.1	-0.1	1					
Ca.H *(mg/l)*	-0.2	-0.2	-0.2	0.9	1				
Mg.H *(mg/l)*	0.1	-0.1	-0.2	0.8	0.6	1			
Chloride *(mg/l)*	-0.3	-0.1	-0.2	0.2	0.4	0.1	1		
Iron *(mg/l)*	0.4	0.3	0.7	-0.3	-0.3	-0.3	-0.2	1	
TDS *(mg/l)*	-0.2	-0.3	-0.3	0.6	0.6	0.3	0.1	-0.1	1

Table 6: Extraction of Principal Component

Component	**Initial Eigenvalues**			**Extraction Sums of Squared Loadings**		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.507	38.967	38.967	3.507	38.967	38.967
2	1.964	21.817	60.784	1.964	21.817	60.784
3	1.043	11.590	72.374	1.043	11.590	72.374
4	1.000	11.106	83.480			
5	.659	7.319	90.799			
6	.430	4.775	95.573			
7	.206	2.288	97.861			
8	.171	1.897	99.758			
9	.022	.242	100.000			

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