Research article

Evaluation of water quality and potential scaling of corrosion in the water supply using water quality and stability indices: A case study of Juja water distribution network, Kenya

Gbëtingan Marien Patern Baloïtcha a,*, Alfred O. Mayabi b, Patrick G. Home c

a Department of Civil Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation (PAUSTI), P.O. Box 62000-00200 Nairobi, Kenya
b Department of Civil, Construction and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. Box 62000-00200 Nairobi, Kenya
c Department of Soil, Water and Environmental Engineering, Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. Box 62000-00200 Nairobi, Kenya

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ABSTRACT

Drinking water quality describes the conditions for water to be accepted as suitable for human consumption. The water quality index is characterized by including, in the assessment process, water quality parameters such as physical, chemical and micro-biological. The availability of adequate management strategies to maintain good quality water has always been a challenge for water utilities. To proffer a solution to this problem, a simple and effective tool that can be used to easily assess the quality of water is required. Water Quality Index (WQI) and Water Stability Index (WSI) are the most reliable tools for assessing water quality and aggressiveness. This study, therefore assessed the water quality, potential scaling and corrosion of the water supply in the Juja water distribution network by using WQI and WSI based on Langelier Saturation Index (LSI). Five sampling locations including the treatment plant outlet and consumption points were selected for physical, chemical and bacteriological water quality analysis and determination of WQI and WSI. It was found that 100% of the collected water samples had Calcium concentrations within the World Health Organization (WHO) and Kenya Bureau of Standards (KEBS) acceptable ranges. Additionally, all the collected water samples had TDS concentrations within the WHO and KEBS acceptable ranges. However, water quality parameters such as Residual Chlorine, E. coli, Alkalinity, and Turbidity deviated from the WHO and KEBS standards. The pH values ranged from 6.29 to 8.06 and were generally within acceptable limits. The WSI ranged between $-3.04$ to $-0.99$, indicating that the water is generally corrosive and may pose a risk to water quality and shorten the lifespan of the network facilities. Generally, the water from the Treatment Plant was of good quality, while at consumption points, JKUAT Main Gate, JKUAT Campus, High Point, and Juja Stage had fair water quality based on the calculated WQI. Also, low concentrations of residual chlorine and E. coli slightly dropped the water quality at all the stations. Overall, the water quality deteriorated in the distribution network and was corrosive throughout the system right from the Treatment Plant based on the WQI and WSI. The water company needs to improve on the water quality chemically by adjusting the Calcium and Alkalinity concentration up to 40 mg/L CaCO3 as recommended for stable water and relook at management strategies of the network to provide better services to consumers.

1. Introduction

Drinking water quality describes the conditions for water to be accepted as suitable for human consumption. Water Quality Index (WQI) includes water quality parameters such as physical, chemical and micro-biological (WHO, Guideline for drinking water quality, 2012). To assess the quality of water using water quality and stability indices, it is pertinent to use safe limits (standards) that have been established by some agencies such as World Health Organization (WHO). The availability of adequate management strategies to maintain good quality water has always been a challenge for water utilities (WHO, Guidelines for Drinking-water Quality, 2008; Abbasi, 2012; Carvalho, 2011). To

* Corresponding author.
E-mail address: baloitchapatern@gmail.com (G.M.P. Baloïtcha).

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provide a solution to the problem, a simple and effective tool that can be used to easily assess the quality of the water is of dire need. The water quality index is the most reliable tool for assessing water quality (Reza, 2010) (Panduranga Murthy, 2009). A set of parameters is used in a mathematical equation to estimate water quality and its suitability for a particular use as domestic, agriculture, and industrial (Omer, 2019). Horton developed the first WQI using 10 of the most common water quality parameters and arithmetic aggregation functions. The method used by Horton (1965) has been progressively modified and improved by various researchers (Tahera Akter, 2016). Water stability index is another useful tool for the chemical assessment of water quality. Water stability is known as the ability of water to either dissolve or deposit minerals which varies with its set of chemical properties (Alsaggar, 2014). In addition, the water stability may influence water quality due to the leaching of certain metals such as chrome, arsenic and lead into the water causing the water to be corrosive, or lead to bacterial growth if the water is scaling in character (Pietrucha-Urbanik, 2017). Therefore, the stability of the water isortant both as a public health concern and as an economic factor on the water distribution facilities (Pietrucha-Urbanik, 2017) (Khosand, 2016). Langelier saturation index (LSI) and Ryznar stability index (RSI) are the most common methods used to assess water stability. These two indices are designed to predict calcium carbonate behaviour in water, although other multivalent metals are also of concern in the water industry (MHW, 2005).

The WQI determination usually follows three major steps which are (1) parameters selection, (2) quality function determination for each selected parameter, and (3) index aggregation using a mathematical equation (Tyagi, 2013). The WQI is a single number that describes the overall quality of the water at any location based on the selected water quality parameters (Dede, 2013) while the Langelier Saturation Index (LSI) uses simple water quality parameters including Temperature, Total dissolved solids, Alkalinity and Calcium concentration for determination. The calculation is also further simplified in the common water pH range of 6–9 (Environmental, 2017). WQI index is a powerful tool that transforms water quality parameters and known information into a simple index value that anyone can understand, including policy decision-makers and water utility managers (Tyagi, 2013) (Katyal, 2011). A study on several water quality indices concluded that the WQIs that use weighted arithmetic average and modified weighted sum best assess the overall water quality (Katyal, 2011). For this study, the weighted arithmetic method of aggregation was used to compute WQI and, similarly, the LSI formula was used for assessing the water stability. One of the advantages of assessing a water quality is that few parameters can be used to describe the state of the water quality (Tyagi, 2013).

Therefore, the present study built up by assessing the water quality and stability of Juja Water Distribution Network (WDN) by using weighted arithmetic WQI and Langelier Saturation Index methods based on the use of some physical and chemical parameters. The selected parameters for the WQI development were based on their significance on the overall water quality as indicated by WHO and the availability of parameter assessment tools. We expect that the findings would be useful for the water utility to improve its management strategy towards the consistent provision of good quality water over time.

2. Methods and materials

2.1. Study area and design

This study was conducted in Juja town, located between Thika and Ruiru and approximately 30 km from Nairobi, Kenya. Juja town lies between the latitude -1.102554 and the longitude 37.013193. It lies at an altitude of 1519m. The climate is warm and temperate. The average annual temperature in Juja is 18.8°C. The average annual rainfall is 1014 mm. Kenya Population and Housing Census: Volume I did in 2019 stated that Juja towns’ population is 300,948 with 148,446 males and 152,480 females. The study was performed on the drinking water supply network of Juja and five sampling points were selected. Several points were chosen to assess the variation in quality as a function of distance between the points and the treatment plant. To have a clear idea of the water quality before the water enters into the distribution system, the treatment plant outlet was selected as one of the sampling points. The selected sampling points were chosen on the main branches of the network. The treated water is being supplied by Ruiru-Juja Water and Sewage Company RUJWASCO which water source was the Ndargo river. The study area is presented in Figure 1, and the different sampling point coordinates and the distance between the treatment plant and the other points are shown in Table 1.

2.2. Water quality characteristics determination

Chemical, Physico-chemical and bacteriological parameters were measured to evaluate the water. The parameters of interest (Measured) are shown in Table 2. These parameters were used both for water quality and stability indices determination.

Water samples were collected from the five sampling points P1, P2, P3, P4, and P5 as illustrated in Figure 1. P1 was located in front of the JKUAT main gate, P2 was located inside the JKUAT main campus, P3 was located at High Point, P4 was located at the treatment plant and P5 was located at Juja Stage.

2.3. Samples collection

Water samples were collected 4 days a week from the five points for sixteen days (13th April to 6th May 2021) during the dry season. The samples were collected from consumer taps thrice daily, respectively at 7 AM, 1 PM, and 6 PM except at the treatment plant where the samples were collected from a tap located within the plant’s plot. Water samples were collected in sterile 1L or 50 mL plastic bottles for Alkalinity, Calcium, and Turbidity tests or E. coli test. Water samples were transported to the laboratory within 30 min and the ones dedicated for E. coli test were transported in an ice chest.

2.4. Parameters determination

Each parameter was tested in triplicates. American Public Health Association (APHA) standard methods of water and wastewater examination were used for the different tests (APHA, 2012). Temperature, pH, Electrical conductivity and TDS were tested immediately onsite using a water quality multiparameter tester, YTRQ; model pH-686. Residual Chlorine was also tested onsite using a water quality tester, SAZOLEY; model PC-102. Calcium was measured using the ethylenediaminetetraacetic acid (EDTA) titration method. Turbidity was analyzed using SGZ-B Portable Turbidity Meter, while E. Coli was tested using the culture method. Finally, the Alkalinity test was done using the titration method.

2.5. Water quality index calculation

The weighted arithmetic method of aggregation was used for the WQI calculation as described by (Tahera Akter, 2016) (Yisa, 2010) (Tyagi, 2014). The method follows three steps. First, selection of water quality parameters where the following parameters were selected; E.coli, TDS, pH, calcium, turbidity and residual chlorine. Secondly, the quality scaling rate for each parameter was calculated by Eq. (1) where qi, Pi and Wi are quality rating scale, the measured value of ith water quality parameter and S is the WHO standard value of ith water quality parameter respectively. Using Eq. (2), the relative weighting for each parameter was determined as the reciprocal of each parameter where Wi is the relative weighting of each parameter. Finally, the third step is aggregation to obtain the WQI as given in Eq. (3).
\[ qi = \frac{P_i}{S_i} 	imes 100 \]  

\[ W_i = \frac{1}{S_i} \]  

\[ WQI = \frac{\sum Wiq_i}{\sum Wi} \]  

2.6. Water stability index calculation

The Langelier Saturation Index LSI was used to assess the water stability. The stability index was expressed using the set of Eq. (4); (4.a) and (4.b).

\[ LSI = \text{pH} - \text{pH}_s \]  

Where LSI, pH, and pHs are Langelier Saturation Index, the measured pH and the Calcium Carbonate saturation point pHs, respectively (Yousefi, 2018) (United States Environmental Protection Agency, 1984). pHs is calculated, assuming the pH range is within 6–9 as follows:

\[ \text{pH}_s = A + B - C - D \]  

Where A is a combination of p-notation for CaCO3 solubility and carbonic acid 2nd equilibrium constants which is the function of Temperature and B is the activity coefficient which depends on TDS.

\[ C = \log[Ca^{2+}] \text{ and } D = \log[Alkalinity] \]  

2.7. Data analysis

Descriptive statistics such as the mean, standard deviation, minimum, and maximum for the different parameters for each selected point were used to analyze the data. By using MiniTab 20.1.2, the confidence interval for the various water quality parameters of interest, WQI and WSI at a confidence level of 95% which helps to appreciate the quality of the parameters was determined.

3. Results and discussions

The minimum, mean, maximum and standard deviation of the parameters (TDS, Residual Chlorine, Calcium, etc) of interest at the five sampling points are presented in Table 3 and similarly, the WHO and KEBS standards are also presented for comparison purposes. The confidence interval, mean and standard deviation of the different water quality parameters of interest, WQI and WSI for the overall study area are presented in Table 4. The recorded values of E. coli, Turbidity and Residual Chlorine were sometimes out of the defined acceptable limits for

| Location                        | Latitude  | Longitude | Distance (meter) |
|---------------------------------|-----------|-----------|------------------|
| JKUAT Main Gate P1              | -1.10143  | 37.0146   | 2768.60          |
| JKUAT P2                        | -1.09457  | 37.01882  | 2053.48          |
| High Point P3                   | -1.09444  | 37.03094  | 861.29           |
| Treatment Plan P4               | -1.08968  | 37.03625  | 0                |
| Juja Stage P5                   | -1.10816  | 37.01693  | 2989.79          |

| Category                  | Parameter                      |
|---------------------------|--------------------------------|
| Physico-Chemical Parameters | Total Dissolved Solid (TDS), pH, Temperature, Turbidity |
| Chemical Parameters       | Alkalinity, Calcium, Residual Chlorine |
| Bacteriological Parameters | Escherichia Coli (E. Coli) |

![Figure 1. Study area.](image-url)
drinking water. However, the other parameters were within the acceptable ranges defined by WHO and KEBS for drinking water. It was also noted that the confidence intervals CIs of the water quality parameters were mainly within the standard except for the E. coli, values which were significant at 95% level of significance as illustrated in Table 4. Table 5 presented the correlation coefficients between the different water quality parameters.

The TDS concentration varied from 25.17 to 71.89 mg/L, and the average values were between 46.30 ± 8.21 and 58.74 ± 6.10 mg/L as shown by Table 3. The TDS concentration in all the samples was below the maximum values 500 and 700 mg/L respectively defined by WHO and KEBS, which means that all the samples were within the acceptable limits.

Temperature is also an essential parameter for drinking water since it can affect the taste, odour, colour etc. Table 3 illustrated that the temperature varied from 15.63 to 25.00 °C with an average value between 22.61 ± 0.85 and 23.73 ± 0.95 °C.
The residual chlorine concentration varied from 0.07 to 0.8 mg/L, with an average value between 0.20 ± 0.05 and 0.23 ± 0.1 mg/L as referred in Table 3. It was noticed that 37.5% of the overall data had residual chlorine values below the ideal value of 0.2 mg/L. The low concentration made the water distribution system vulnerable to microbial contamination which can be noted by the presence of E.coli in the water samples at time. The decrease of the Residual Concentration concentration within the system could be associated with organic sediments entrained in the water from pipes which increases the chlorine demand. Furthermore, the growth of biofilm such as E.coli could also be another source of the high chlorine demand.

Turbidity had a minimum value of 0.65 NTU, while the maximum value was 13.73 NTU. Table 3 presented that the recorded values had the mean varying between 4.76 ± 1.21 and 5.69 ± 2.76 NTU. A total of 49.75% of the collected samples exceeded the acceptable limit defined by WHO and KEBS. Among this 49.75%, P1 got the highest rate of 20%, followed by P2 8.5%, then P4 and P3 had 7.5% respectively and P5 had 6.25%. It was noted that the high turbidity values do not affect the overall WQI, the rating assigned to this parameter while computing the WQI could justify that fact.

Calcium concentrations had a maximum of 10.23 mg/L and a minimum value of 5.18 mg/L as presented in Table 5. Calcium and Alkalinity are known as a stabilizers of the pH in water, but they have to be maintained at certain levels to properly play their roles (WHO, Guidelines for Drinking-water Quality, 2008). Despite the concentrations of the calcium being within the standards, it is recommended to maintain the calcium concentration at 40 mg/L CaCO₃ to ensure a proper chemical reaction with other parameters that affect the stability of the water. Table 5 showed that Calcium and Alkalinity had a significant correlation with R = 0.55. The effect of the failure of the calcium concentration being maintained at 40 mg/L CaCO₃ was evident in the fluctuating water stability recorded in all the water distribution network.

Alkalinity concentrations were between 9.78 mg/L CaCO₃ and 40.89 mg/L CaCO₃ while the average values were between 29.97 ± 4.48 and 31.28 ± 3.65 mg/L CaCO₃ as shown by Table 3. It was noted that about 54.5% of the water samples alkalinity were within the defined range of WHO and KEBS and the other sample values were below the minimum of 30 mg/L CaCO₃ defined by WHO. The minimum concentration (9.78 mg/L CaCO₃) was far below the lower value (30 mg/L CaCO₃) of the range defined by WHO. According to the results, the low concentration of Alkalinity recorded at time might concern the water stability since it is recommended that the Alkalinity concentration be maintained at 40 mg/L CaCO₃.

The results in Table 3 showed that E. Coli was present in some water samples and a maximum value of 66,000 CFU/100 mL was recorded with the average value ranging between 1708 ± 3003 and 3271 ± 6364 CFU. It is clearly stated by WHO and KEBS that in 100mL of water sample, there must be no coliform. Table 5 showed that Residual Chlorine, Calcium, Alkalinity, Turbidity, and pH had relationships with E.coli. Since these parameters had statistically significant correlation coefficients, a great attention on these could result in the partial resolution of problem. E.coli is generally from various sources such as feces (infected humans or animals), waste, sewage overflow, polluted storm water, etc (WHO, Guidelines for Drinking-water Quality, 2011). The E. coli in the water samples can be associated with the pipe corrosivity that happened during the study period resulting in an intrusion of waste. Activities conducted during temporal maintenance within the distribution network could also have contributed to the intrusion of waste. Another probable reason could be the contamination of the taps by the occupants. Some random samples of tap water were collected after the defined period of study and they were exempt from E. coli which suggested that the E.coli was not continuously present in the system. This confirms the suspected sources mentioned above. Despite the flush out system available for the cleaning of the pipes after every intervention within the network, the water company still has to take further measures to improve and provide reliable quality water to consumers. This study however recommends that the consumers should boil their water before drinking.

The pH values had a minimum value of 6.29 and a maximum of 8.06 as illustrated in Table 3. Most of the sampled waters’ was within the acceptable range of WHO and KEBS. The maximum pH value was within the required range while the minimum pH value was slightly less than the lower value (6.5) provided in the standards. It is preferable to maintain pH below 8 to ensure proper disinfection. However, a water pH less than 7 or precisely 7 could lead to the corrosion of the network facilities (WHO, Guidelines for Drinking-water Quality, 2011). The LSI gives a reasonably correct indication of corrosivity in a water of pH range 6.5–9.5. The percentage of the water samples lying within the defined range of LSI was about 98% of the total collected samples. Based on the collected data, it can be seen that the water ranged from slightly acidic to slightly alkaline. pH does not directly impact human health, but careful control of it needs to be established to ensure its great chemical reaction with other parameters (WHO, Guidelines for Drinking-Water Quality, 2004).

The calculated WQI showed the following rates 1.25 %, 63.33 %, 23.75 %, 2.92 %, 5 % and 3.75 % respectively for the quality classes defined in Table 6 which are excellent, good, fair, marginal, poor, and very poor. E.coli was a key water quality parameter that needs great attention. Overly, water quality was found fair at all the collection points except at the treatment where the water quality was found good as shown in Table 7. According to the findings in Table 7, it is evident that the

### Table 5. Correlation coefficient between the water quality parameters.

| TDS | Residual Chlorine | Calcium | Turbidity | pH | E. Coli | Alkalinity | Temperature |
|-----|------------------|---------|-----------|----|---------|------------|-------------|
| TDS | 1                |         |           |    |         |            |             |
| Residual Chlorine | 0.03 (*) | 1 |         |    |         |            |             |
| Calcium | -0.01 (*) | -0.09 (*) | 1 |      |         |            |             |
| Turbidity | 0.12 (*) | 0.10 (*) | -0.06 (*) | 1 |         |            |             |
| pH | -0.03 (*) | -0.08 (*) | 0.22 (*) | 0.06 (*) | 1 |         |             |
| E. Coli | -0.20 (*) | -0.20 (*) | 0.14 (*) | -0.16 (*) | 0.21 (*) | 1 |             |
| Alkalinity | -0.01 (*) | 0.00 (*) | 0.55 (*) | 0.03 (*) | 0.24 (*) | 0.17(*) | 1 |
| Temperature | 0.20 (*) | 0.03 (*) | -0.08 (*) | -0.01 (*) | 0.11 (*) | 0.01 (*) | 0.18 (*) | 1 |

*The correlation is statistically significant at the level of 0.1 (Two tailed) * The correlation is not statistically significant at the level of 0.1 (Two tailed).

### Table 6. Water quality classification based on the calculated WQI.

| WQI Range | Classification |
|-----------|----------------|
| <85       | Excellent      |
| 85 < WQI ≤135 | Good        |
| 135 < WQI ≤175 | Fair       |
| 175 < WQI ≤200 | Marginal  |
| 200 < WQI ≤300 | Poor       |
| >300      | Very Poor     |
Table 7. Summary of the study areas’ water quality based on WQI and WSI calculated.

| Location                | WQI   | Quality Status   | WSI   | Quality Status   |
|-------------------------|-------|------------------|-------|------------------|
| High Point P3           | 151.15| Fair             | -2.12 | Highly Aggressive |
| Juja Stage P5           | 141.57| Fair             | -2.00 | Moderately Aggressive |
| JKUAT Main Gate P1      | 146.95| Fair             | -1.92 | Moderately Aggressive |
| JKUAT P2                | 144.66| Fair             | -2.03 | Highly Aggressive |
| Treatment Plant P4      | 131.11| Good             | -1.99 | Moderately Aggressive |

Table 8. Summary of WSI classification.

| WSI Range  | Classification                  |
|------------|---------------------------------|
| -2 ≤ WSI < 0 | Moderately Aggressive, Under Saturated |
| WSI < -2     | Highly Aggressive, Under Saturated |
| WSI = 0      | Saturated Water, Water at balance  |
| WSI >0       | Scaling Water, Super Saturated   |

water quality was most of the time suitable for drinking when leaving the Treatment Plant P4 but along the way, it can decrease in quality. At times, the drop in quality can be associated to the low concentrations of residual chlorine at the time and also the presence of E. coli at all the stations.

The lowest and the highest value of WSI were -3.04 and -0.99, respectively as shown in Table 3. It was noted that 50.83% of the sampled waters were highly aggressive and 49.17 % were moderately aggressive. Water samples containing low pH, calcium, and alkalinity are more corrosive, which ends to be correlated with a Langelier Index (WHO, Guidelines for Drinking-water Quality, 2008). All the collected water samples were under saturated according to the classification illustrated in Table 8 and the summary results presented in Table 7. This fact can be justified by the water samples having low pH, low calcium, and Alkalinity concentrations. Furthermore, the correlation coefficients in Table 5, established between the water quality parameters involved in the calculation of the WSI showed that all the parameters were interrelated and once one of them failed to fit the standards, the global stability was then in doubt. There was no significant variation of the WSI between the different points and this is an alert that serious adjustment must be made at the treatment plant to avoid a phenomena whereby the facilities’ internal surfaces may start being corrosive and adversely affect the water quality.

4. Conclusions

From this study carried on the Juja WDN, based on the calculated WQI, we recorded the following percentages 1.25 %, 63.33 %, 23.75 %, 2.92 %, 5 % and 3.75 %, respectively for the quality classes of excellent, good, fair, marginal, poor, and very poor. It was noted that the water quality generally deteriorates during the water conveyance from the Treatment Plant to the other selected points. The drop of the quality was associated with the occasional decrease of the chlorine residual concentration, the presence of E. coli at the time, the WDN components age, and the TDS concentration in some water samples. Moreover, an adjustment needs to be made to eliminate the recorded E. coli and increase the water quality. The study also reveals that water in the entire system is corrosive and requires some adjustments at the treatment point. This adjustment may entail increase of the Alkalinity and Calcium concentrations up to 40 mg/L CaCO₃ each, and a pH close to neutral. To improve on recontamination of the water in the system, the management should assess chlorination level and consider a well-organized system of network maintenance schedule to ameliorate against pipes and intrusion of contaminated water. Since the study showed that pH, Alkalinity, Calcium, TDS and E. coli are the most important parameters, an alternative solution could be the use of sensors to have real-time monitoring of these parameters, which are good tools of alert that can be used to quickly take corrective actions when needed. From this study, it was noted that the individual consideration of water quality parameters is not enough to state the quality of water and it was found that WQI and WSI are great tools to critically assess the quality of water and the potential of scaling and corrosivity to impact on the WDN facilities life and water quality. Further studies can be carried out on the Juja WDN to identify the best management system using advanced tools such as real-time monitoring and augmented reality to achieve high-quality services for the water supply to consumers.

Declarations

Author contribution statement

Gbétingan Marien Patern Baloïtcha: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Alfred O. Mayahi: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Patrick G. Home: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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