Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.27262

226 (2021) 52–61
June

Stability evaluation of Tigris River raw water and treated drinking water from main water treatment plants within Mosul City

Musab A. Al-Tamir

Environmental Engineering Department, College of Engineering, University of Mosul, Mosul, Iraq, email: musabaltamir@uomosul.edu.iq

Received 10 November 2020; Accepted 24 March 2021

ABSTRACT

Corrosion and scaling are the main factors affecting raw water supply resources and treated water produced from Water supply treatment plants (WTPs), resulting in operational, economic and health issues. Mosul City, North of Iraq, depends on Tigris River as the only surface water supply source for its municipal uses. Water quality parameters were taken from eight locations on Tigris River that represent the intake of the main WTPs providing water for Mosul City; and for the water produced from these plants. Langelier and Ryznar indices were calculated to evaluate water stability. Results showed that the average value of Langelier Saturation Index (LSI) for raw water was 0.23 (±0.31) and 0.08 (±0.30) for treated water. Approximately 78% of raw water samples and 59% of treated water samples were classified as scale forming according to LSI, although Tigris River raw water and treated water are not potentially aggressive even when LSI value was less than zero. The average value of Ryznar Stability Index (RSI) for Tigris River raw water was 7.25 (±0.34) and for produced water was 7.42 (±0.33). Both raw and treated water were aggressive and likely corrosive according to RSI classification. Duncan analysis of variance (ANOVA) statistical analysis for RSI showed non-significant differences among the means of most of Tigris River locations. However, water is more saturated with $CaCO_3$ at the river downstream. Paired *t*-test analysis of RSI revealed a significant difference between raw water and treated water stability. Again, Duncan ANOVA statistical analysis of treated water RSI showed significant differences between produced water from WTPs plants; which reflect the deference of their operational style. All statistical tests were made at the threshold for significance at 95% confidence.

Keywords: Mosul City; Tigris River; Langelier Saturation Index; Ryznar Stability Index; Stability of water

1. Introduction

The ability of water to either corrode or scale minerals is known as water stability, this depends on water saturation extent with minerals (especially calcium, magnesium, chlorides, and sulfate which represent the major part of the total dissolved solids in natural water), pH, temperature, water hardness, and water alkalinity. Most stability indices focus on these characteristics to determine the water stability. Furthermore the scaling and corrosiveness depends upon the properties of the contact surfaces [1,2].

The corrosive water increases the dissolvability of calcium, magnesium minerals, and harmful metals from plumbing utilities, such as lead and copper. The exposure of fixtures surfaces to corrosive water increases the risk of having manufacturing metals, such as lead, dissolved in the water supply. To avoid high levels of lead in water, USEPA regulations restricted the use of lead-based materials in water supply and plumbing fixtures. Practically, water is considered aggressive if its Langelier Saturation Index (LSI) is less than (–1.5) [1,3,4].

The performance of water treatment plants (WTPs) in Mosul was monitored and evaluated extensively. Matmara [5], Hassan et al. [6], Al-Obaidy [7], Al-Naiemy [8], and Fadhel and Hamid [9] examined the consequent units in many WTPs and its efficiency for turbidity and microorganisms removal. Al-Tamir [10] made a comparation for the performance of WTPs in Mosul and ranked the WTPs according to the raw water quality entered to the plant and the turbidity removed. Other studies were conducted dealing with water quality of Tigris River within Mosul City and Mosul Dam to the upstream to the river [11–13]. To the best knowledge of author, the stability of Tigris River water within Mosul and treated water from WTPs within Mosul City was not considered in all of the studies conducted till now. However, some studies were conducted in other parts of Tigris River, like Alsaqqar et al. [14] who evaluated the stability of water produced from water treatment plant in Baghdad, the capital of Iraq, LSI and the Ryznar Stability Index (RSI) were used to evaluate the water stability and researchers found that the treated water from these WTPs were corrosive and not safe for the domestic uses. Abdulhussein [15] investigated the stability of Euphrates River treated water produced from six selected WTPs in Babil Governorate, south of Iraq. LSI, RSI, Puckorius Scaling Index (PSI), and Aggressive Index (AI) were used to estimate the stability of treated water and the treated water was moderate corrosive and oversaturated with $CaCO_3$. Many studies were carried out to evaluate the stability of surface and ground water out of Iraq. García-Ávila et al. [16] studied the stability of drinking water in the Azogues City at Ecuador using LSI, RSI, and PSI indices. The study indicated that the drinking water was corrosive in the study region, Al-Rawajfeh [17] by monitoring the scale-forming of brine solution noted that the thickness of $CaCO_3$ deposition rate decreases with increasing pH values and increases with increasing temperature, salinity, and concentration factor. Mirzabeygi et al. [18] investigate the drinking water distribution system in Torbat Heydariye, using LSI, RSI, PSI, Larson-Skold index (LS), and AI to evaluate the stability of water. Results showed that the drinking water of the study area is corrosive in most conditions, indicating that sulfate, chloride anions, and water temperature are the most important parameters of water corrosive tendency at the study area. Yousefi et al. [19] evaluated the stability of 30 well in Jolfa City (East Azerbaijan Province, Iran), by using the Langelier, Ryznar, Puckorius, and aggressive indices. And concluded that the water of the wells was corrosive according to the used indices. Al-Rawajfeh and Al-Shamaileh [20] described various stability indices to assess the corrosivity and scale formation for tap water in Tafla City, South Jordan, using LSI, RSI, and the calcium carbonate precipitation potential indices. Researchers found that all used indices indicated to corrosion condition of the water and the water samples exhibited high concentrations of major anions Cl^-, SO_4^{2-}, and HCO_3^- and major cations Ca^{+2} and Mg^{+2}. Kumar et al. [21] after noticing high scale formation with a high record of kidney-stone in Thanjavur City and its suburbs, studied calcium content, its desirability level, and the corrosion/scaling coefficients. LSI and RSI were used to estimate scalability and corrosivity of water, and they referred that stability of water is an important consideration for potability of water which are the functions of other soluble ions present in the water. Abbasnia et al. [22] evaluated drinking water quality in villages of Chabahr City, Sistan and Baluchistan Province in Iran by using WQI technique and the water scaling and corrosion potential of the water by assisting from LSI, RSI, PSI, LS, and AI stability indices they illustrated that 25% of water samples could be considered as excellent water, 50% as good water, and 25% fall in poor water category. Again Abbasnia et al. [23] evaluated ground water quality in the Sistan and Baluchistan Province in Iran, for water stability they depended upon LSI, RSI, PSI, LS, and AI to determine water suitability for industrial purposes, according to their results the water sources including on their study were corrosion based to the Larson-Skold Index, low and light corrosion according to the RSI, and less corrosive according to AI and PSI and so forth. Asghari et al. [25] estimated stability in water supply networks of Khoy and Makou at Northwest of Iran; to evaluated water stability they depended LSI, RSI, AI, LS, and PSI indices, their study revealed a significant differences in means of LSI, RSI, PSI between cold and warm seasons of the year in Khoy samples and a significant differences in means of RSI, PSI, and AI between cold and warm seasons of the year in Makou samples were they used paired *t*-test, finally the researchers referred that water chemical characteristic cannot imitate chemistry of water and balance, even if it conforms with drinking water standards, then with balancing water the economic losses and health impact can be reduced by modification of water pH.

The main objective of this study is to evaluate the stability of Tigris River water within Mosul City sector and the drinking water produced from WTPs furnishing water to the city. All water quality data were collected from WTPs influent (intake of the plant on Tigris River) and product water from each plant. LSI and RSI were employed to estimate corrosivity and scaling tendency of raw and drinking water, this study represent the first one globally and indigenously about the scalability and corrosivity of Tigris River raw water and drinking water within Mosul City.

2. Mosul City location

Mosul is one of the main cities of Iraq with a population of around 2.7 million. It is located 400 km north of Baghdad, the capital of Iraq, at 36.34°N 34.13°E and elevate by 223 m above the sea level [27]. Tigris River pass through the city and represents the main water supply resource for its population. There are nine Water Supply Treatment Plants within Mosul City, all of them take water directly from Tigris River Fig. 1 and Table 1 [10].

3. Methodology

There are many techniques to estimate water stability, among these are water stability indices. In this study, LSI and RSI indices were adopted to evaluate stability. These indices are widely used in many studies for the evaluation of water stability as showed in the previous paragraphs, LSI was invited from 1936 by Langelier [28] to discover the ability of water for scaling or corrosiveness, LSI was improved by Ryznar in 1944 [26] to present a new index

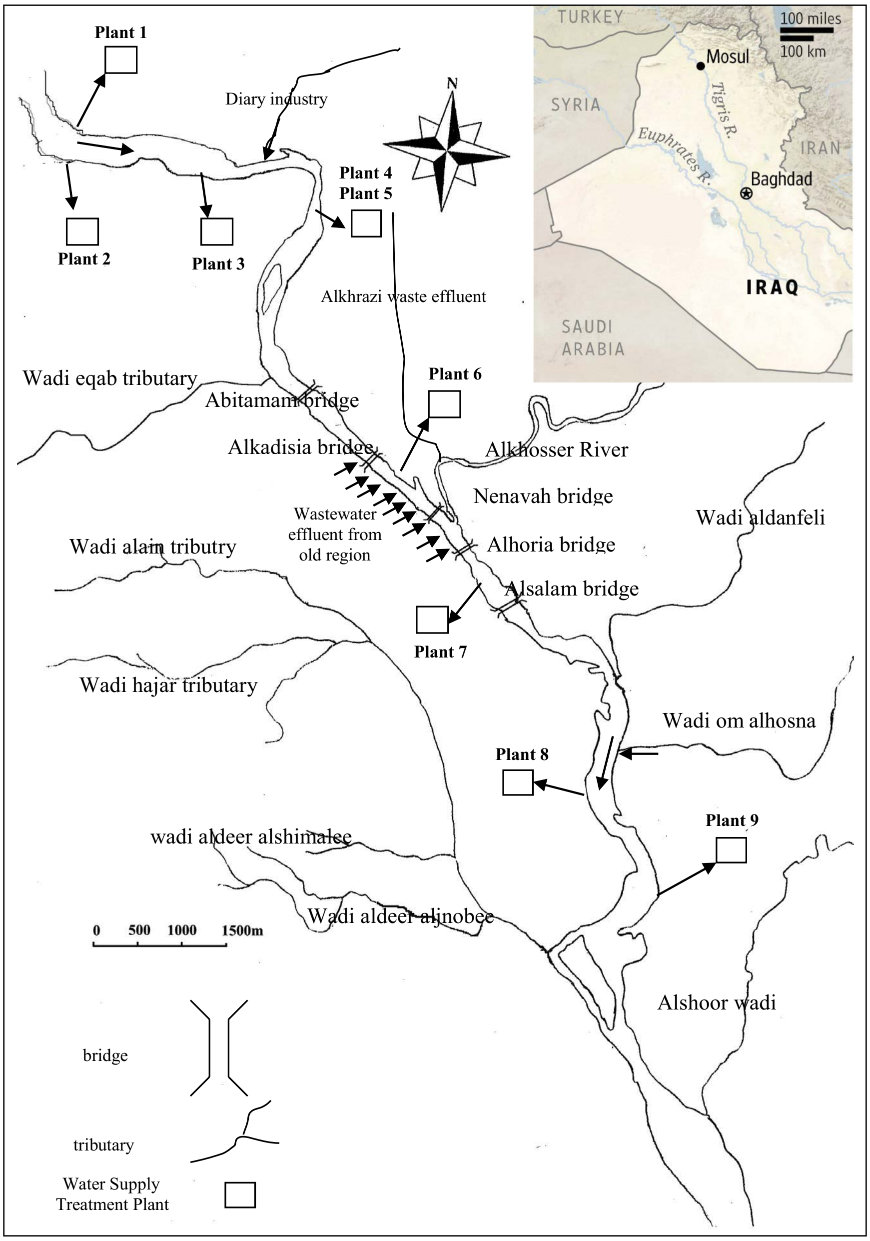

Fig. 1. WSTP positions on Tigris River, Mosul City, Iraq.

Table 1
Details of WTPs working in Mosul City

No.	Name of plant	Position on Tigris River	Productivity ($m^3/d \times 10^3$)
1	Al Aiser Al Jaded (Al Quba)	Alkuba region on the left Tigris River bank	300
2	Al Aimen Al Jaded	Ihlelah region on the right Tigris River bank	380
3	Al Aimen Al Kadem (Al Mouhed)	Msherfah region on the right Tigris River bank	180
4	Al Aiser Al Kadem	Alarabi district on the left Tigris River bank	90
5	Al Aiser Al Taosea	Alarabi district on the left Tigris River bank	100
6	Al Zuhoor	Alzohoor district on the left Tigris River bank	18
7	Al Danadan	Al Danadan region on the right Tigris River bank	10
8	Al Ghzlani	Al Ghzlani region on the right Tigris River bank	45
9	Al Saheroon	Yarmja region on the left Tigris River bank	36

named RSI by which a comparison between several water samples with different stabilities can be made, both LSI and RSI are widely used in water studies for their simplicity and reliability. In this study, LSI was used to check the water scaling or corrosiveness ability, while RSI was used to compare the water stability of raw water with treated water produce from WTPs and the raw water and treated water between different position on Tigris River and different WTPs (Fig. 2).

Eqs. (1)–(5) were used to calculate LSI and RSI:

$$\text{LSI} = \text{actual pH of the water} - \text{pHs} \quad (1)$$

where:

pHs is the pH of calcium carbonate saturation, Larson and Buswell [29] derived Eq. (2) to calculate pHs.

$$\text{pHs} = \log\frac{K_s}{K_2} - \log\left[\text{Ca}^{++}\right] - \log\left[\text{alk.}\right] + 9.3 + \frac{2.5\sqrt{\mu}}{1+5.3\sqrt{\mu}+5.5\mu} \quad (2)$$

where [Ca^{++}] and [alk.] are concentration of calcium and alkalinity in mg/L as Ca and $CaCO_3$ respectively; K_s is the solubility product of calcium carbonate; K_2 is the second dissociation constant of carbonic acid; μ is the ionic strength of the solution, for natural water of less than 500 mg/L mineral; μ = 0.000025 times the total mineral contents.

K_s and K_2 are dependent of the temperature, the temperature dependent Eqs. (3) and (4) [30–32]:

$$\log K_s = -171.9065 - 0.077993T + \frac{2{,}839.319}{T} + 71.595\log T \quad (3)$$

$$\log K_2 = -107.8871 - 0.032528T + \frac{5{,}151.79}{T} + 38.92561\log T - \frac{563{,}713.9}{T^2} \quad (4)$$

where T is the absolute temperature in Kelvin.

RSI is a modification of LSI to mark the degree of water stability can be calculated from Eq. (5) [26].

$$\text{RSI} = 2\text{pHs} - \text{actual pH} \quad (5)$$

RSI in this study was used to compare water stability between selected locations and plants established on Tigris River within Mosul City sector, Some researchers used RSI values to classify and describe water stability as shown in Table 2 [14–16,33].

4. Discussion

Table 3 reveals the descriptive statistics for selected water quality parameters of Tigris River raw water and treated water produced from the WTPs working in Mosul City and for the calculated LSI and RSI. The following paragraphs will discuss the variation of LSI and RSI according to the river positions and plants for raw and treated water.

5. Raw water

Fig. 3 shows the percentage of raw water samples with LSI values greater than zero (water is scale forming) and raw water samples with LSI less than zero (abrasive

Table 2
Water stability classification according to RSI

RSI value	Stability description
<5.5	Highly scale – formation
5.5–6.0	Relatively scale – formation
6.2–6.8	Neutral
6.8–8.5	Low corrosive
>8.5	Highly corrosive

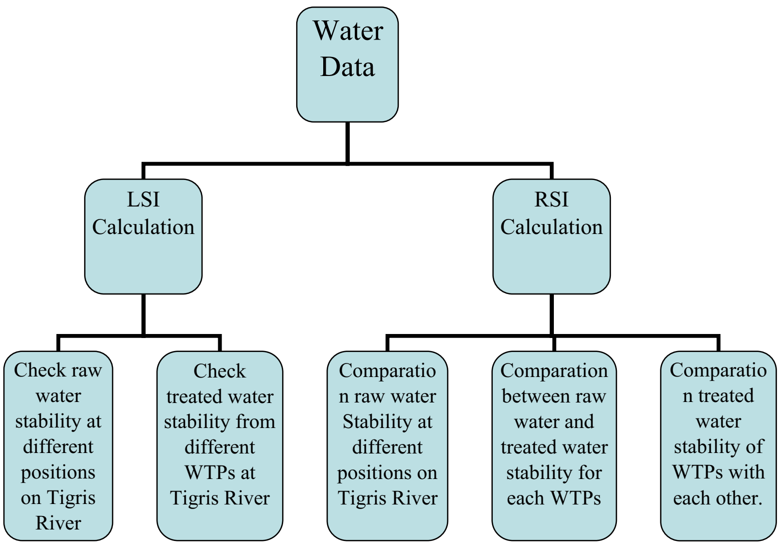

Fig. 2. Study methodology.

Table 3
Descriptive statistics for the quality of Tigris River raw water and treated water

Water type	Tigris River raw water				Treated water			
Descriptive parameter	Min.	Max.	Mean	Std. deviation	Min.	Max.	Mean	Std. deviation
Turbidity (NTU)	2	250	12.48	21.44	0.4	20	2.87	1.63
Temp. (°C)	18	23	20.93	1.41	18	23	20.89	1.4
pH	7	8.1	7.59	0.24	6.9	8	7.47	0.26
TDS (mg/L)	238	338	275.17	19.06	234	398	271.69	21.78
E.C. (μmohs/cm)	378	546	435.5	31.5	367	554	429.2	33.71
Total Alk. as $CaCO_3$ (mg/L)	126	161	135.12	6.01	125	160	133.28	6.27
T.H. as $CaCO_3$ (mg/L)	176	228	195.28	13.21	174	235	193.61	13.74
Na^{+1} (mg/L)	5.1	13	7.82	1.69	5.7	13.5	8.7	1.73
K^{+1} (mg/L)	1.2	2.35	1.77	0.3	1.1	2.3	1.68	0.29
Ca^{+2} (mg/L)	18	68	51.84	4.07	44	74	50.95	3.72
Mg^{+2} (mg/L)	11	21.35	15.96	2.5	12	176	16.87	11.06
Cl^{-1} (mg/L)	12	20	16.79	1.67	14	25	18.84	1.74
SO_4^{-2} (mg/L)	37	85	56.01	11.64	37	87	54.34	11.61
LSI	–057	0.95	0.23	0.307	–0.59	0.74	0.08	0.3
RSI	6.5	8.42	7.25	0.34	6.7	8.17	7.42	0.33

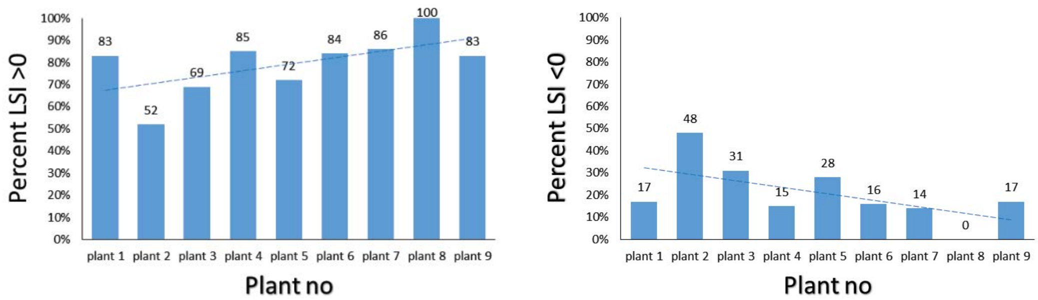

Fig. 3. Percent of LSI more and less than zero of raw water at each plant.

water). It is clear that more than 50% of raw water samples to 100% in some positions fall within the range above zero. The total percentage of raw water samples with LSI values more than zero is 78% for all positions combined with each other, with maximum LSI value of 0.95. The fraction of raw water samples with LSI less than zero is 22% for all sits, with minimum LSI value of –0.57.

Tigris River water tends to be saturated with $CaCO_3$ due to water quality composition as shown in Table 3. It is also characterized by high alkalinity and Ca hardness due to the geological formation of Tigris River basin. The main geological formations in Mosul City region are Fatha formation (Middle Miocene) and Injana formation (Upper Miocene), rich with limestone, gypsum and calcite rocks. As a result, the carbonite and bicarbonate levels in Tigris River water and ground water around Mosul City region are high [12,34,35].

Fig. 4 shows the fluctuations of LSI with time, temperature and average monthly rainfall intensity within Mosul City in years of 2018 and 2019. From this figure it can be concluded that the temperature and LSI were negatively correlated, indicating a good negative correlation between the temperature and LSI close to 0.5 (Table 4). This reflects the strong relationship between water stability and seasonal variation upon the river; where during cold seasons the river water goes to be scale forming while in hot weather it tends to be corrosive.

However, the relationship between rainfall and LSI is unclear, with positive correlation of 0.25 or less, but this weak correlation flashes to the effect of the runoff from the catchment areas below the Mosul Dam reservoir on the Tigris River 50 km upstream to the north of Mosul City. This runoff is enriched with agricultural and human waste carried from these catchment areas [12,13]. In contrast, Fig. 4 shows that the trend lines of the LSI values for all positions is decreased with time during 2018 to 2019. This could be due to the heavy rainfall through these two years especially in 2019 that dilute the water of the Mosul Dam which reflect Tigris River water quality.

RSI is used in this study to compare the stability of raw water at each plant position. Table 3 shows the descriptive statistics for RSI of both of raw and treated water for all plants. Fig. 5 shows the comparison between RSI values of raw water at each plant position. The RSI values

Fig. 4. LSI and temperature and rainfall within Mosul City vs. time in months through 2018–2019 for raw water.

Table 4
Correlation between LSI and rainfall and LSI and temperature

Plant no.	Correlation between LSI and rainfall	Correlation between LSI and temperature
Plant 1	0.177	–0.494
Plant 2	0.0045	–0.197
Plant 3	0.287	–0.535
Plant 4 and Plant 5*	0.0297	–0.441
Plant 6	–0.0283	–0.387
Plant 7	0.0919	–0.173
Plant 8	0.25	–0.54
Plant 9	0.172	–0.547

*Plant 4 and Plant 5 contribute with the same raw water intake.

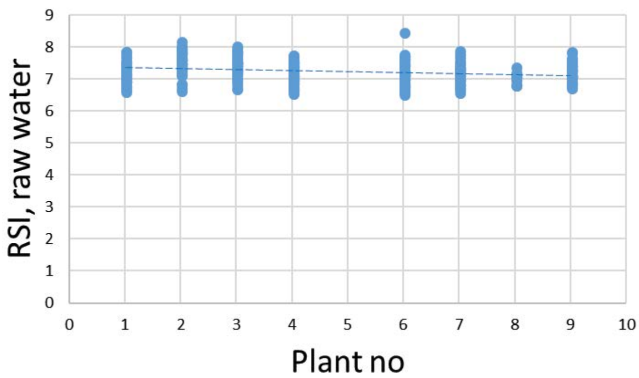

Fig. 5. RSI for raw water at each plant.

demonstrate that the raw water for all positions are from saturated to slightly under saturated with $CaCO_3$. Post hoc Duncan one way analysis of variance (ANOVA) test was run on RSI of the raw water for all samples points on Tigris River to test the significant difference in mean between these points. The significant differences among Plant 2 and Plant 3 and other plants (1, 4, 5, 6, 7, 8, 9) are clear which are in another separate group with no significant difference between their RSI means as shown in Table 5. In general, Figs. 3–5 and Table 5 revealed that the trend of stability of Tigris River raw water leaning slightly to be more saturated with $CaCO_3$ towards downstream of the river from north to south of Mosul City along with the river stream. This is because of the wastewater effluents that discharge directly to the river without any treatment as shown in Fig. 1.

6. Treated water

Fig. 6 represents the percentage of water produced from the WTPs with LSI less than and more than zero. It is obvious that LSI values with greater than zero for raw water are more than those of treated water by approximately 10%–25%. This could be attributed to water equilibrium, affected by many reactions through the processes of water treatment. The main process impacts water balance is the coagulation process, which always changes the free CO_2 and consumes alkalinity, thus decreasing the scaling ability of water process (each gram of alum consumes 0.51 g of water alkalinity; Eq. (6)). In addition, air binding phenomenon during filtration due to suction pressure draw the free CO_2 and shift the equilibrium. Also, chlorination process forms a mixture of hydrochloric acid and hypochlorous acid in water [Eq. (7)] to drop water pH. In addition to the treatment processes, the growth of algae and/or bacteria in the basins, pipes, and channels at the different parts of the WTP may either, directly or indirectly affect CO_2 consumption/production. The change of temperature through WTP units change the stability [1,29,36,37].

Table 5
Duncan ANOVA analysis for raw water RSI between WTPs position

Plant no.	*N*	Subset for alpha = 0.05	
		1	2
8	13	7.0101	
7	36	7.0512	
6	64	7.1509	
4 and 5	47	7.1515	
1	35	7.1706	
9	42	7.1880	
3	52		7.3952
2	44		7.4932
Sig.		0.087	0.280

$$\underbrace{Al_2(SO_4)_3 \cdot 14H_2O}_{\text{alum}} + \underbrace{3Ca(HCO_3)_2}_{\text{Calcium alk.}} \Leftrightarrow 2Al(OH)_3 \downarrow + 3CaSO_4 + 6CO_2 + 14H_2O \quad (6)$$

$$\underbrace{Cl_2}_{\text{chlorine}} + H_2O \Leftrightarrow \underbrace{HOCl}_{\text{hypochlorous acid}} + \underbrace{HCl}_{\text{hydraulic acid}} \quad (7)$$

Total percent of treated water samples with LSI more than zero is 59% for all plants, with maximum LSI value of 0.74, and the percent of treated water samples with LSI less than zero is 41% for all plants combined together with minimum LSI value of –0.59.

In general, the treated Tigris River raw water and drinking water produced within Mosul City is not potentially

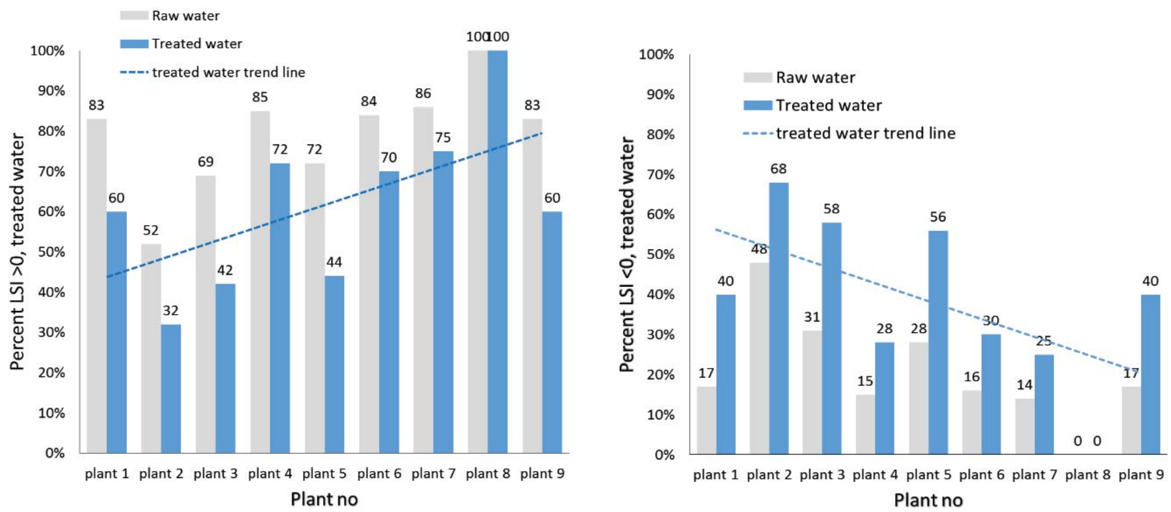

Fig. 6. Percent of LSI more than and less than zero for raw and treated water of the WTPs within Mosul City.

aggressive according to LSI values (all values are more than –1.5) [1,3,4].

Fig. 7 shows RSI values for treated water at each plant. Combining the values of RSI between range of 6.5–8.17 or the water is neutral to low corrosive based on Ryznar classifications.

Paired *t*-test were handled to verify the difference in means for raw and treated water at each individual plant (Table 6) the test confirmed the differences in means for all plants at confidence of 0.05; we can say that the treatment affect significantly upon the stability of water.

Contrary, Duncan ANOVA analysis Table 7; sets the plants in four groups that illustrate the significant differences of product water stability from each plant with another plants the variation of plants products referred to the different doses of alum and chlorine used at each plant through the treatment processes.

7. Conclusion

This study is mainly concerned with the stability of Tigris River while passing through Mosul City sector and the stability of drinking water in the city which depends completely on Tigris River on its supply. The indices used were LSI and RSI, and results showed that 50%–100% of the samples taken from eight position on Tigris River through years 2018–2019 had LSI > 0 with maximum value of 0.95 and minimum value equals –0.57 by which the water

Table 6
Calculated t and p-value for each treatment plant paired t-test

Plant no.	Calculated t-value	p-value
Plant 1	–8.65	0
Plant 2	–11.77	0
Plant 3	–15.74	0
Plant 4	–16.98	0
Plant 5	–14.51	0
Plant 6	–8.22	0
Plant 7	–18.17	0
Plant 8	–7.27	0
Plant 9	–8.34	0

*the value of p for all tests at all plants are less than 1×10^{6}.

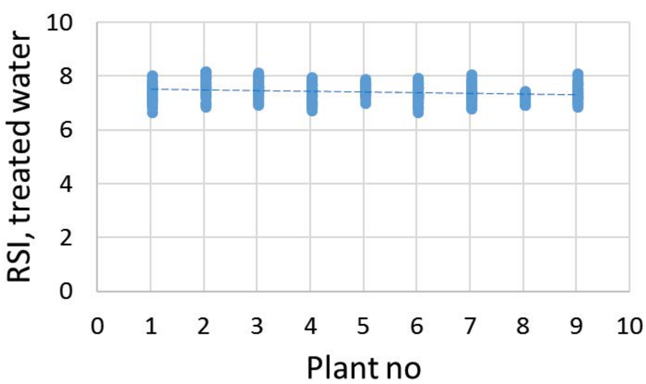

Fig. 7. RSI of treated water for each plant.

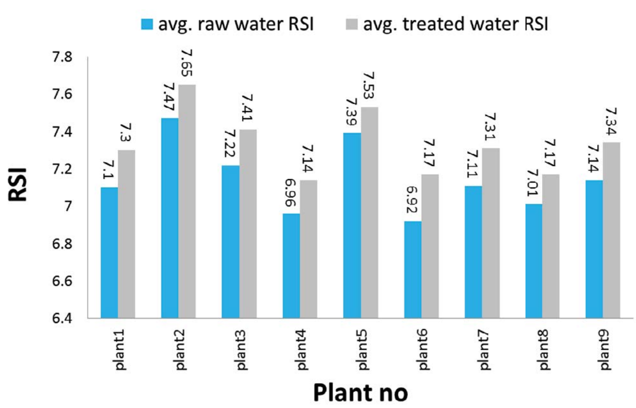

Fig. 8. RSI of raw and treated water at each WTP under the study.

Table 7
Duncan ANOVA analysis for treated water RSI between WTPs

Plant no.	N	Subset for alpha = 0.05			
		1	2	3	4
9.00	42	7.2483			
6.00	64	7.3166	7.3166		
4.00	47	7.3301	7.3301		
1.00	35	7.3677	7.3677		
7.00	36		7.4194	7.4194	
8.00	13		7.4484	7.4484	
3.00	52			7.5633	7.5633
2.00	44				7.6470
Sig.		0.144	0.115	0.066	0.258

considered not aggressive. According to RSI, Tigris River water is classified as saturated to slightly under saturated with $CaCO_3$. Furthermore, the water tends to be more saturated with $CaCO_3$ to the downstream of the river to the south of Mosul City. Drinking water produced from WTPs in Mosul was 10%–25% more corrosive than Tigris River raw water affected by treatment units process at WTPs, but still not potentially aggressive according to LSI values. For RSI drinking water assort as neutral to low corrosive with maximum value of RSI equals 8.17 and minimum value of 6.7. The statistical analysis confirms a difference between water stability for each WTP due to their operations inequality. As a recommendation, no further treatment is needed for the water regarding stability at the present time.

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