RESEARCH ARTICLE

SABRAO Journal of Breeding and Genetics
56 (5) 2175-2183, 2024
http://doi.org/10.54910/sabrao2024.56.5.40
http://sabraojournal.org/
pISSN 1029-7073; eISSN 2224-8978

APPLICATION OF MATHEMATICAL MODEL TO ASSESS THE IRRIGATION WATER QUALITY OF THE TIGRIS RIVER IN MOSUL CITY, IRAQ

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SUMMARY

The promising study aimed to periodically monitor the environmental certainty of the Tigris River water and its suitability for irrigation using the water pollution index model in Mosul City, Northern Iraq. The different identified sites were five points, starting from the city entrance of Mosul (Mushairfa area) to the Albusief area where the river leaves the city. The collection of water samples occurred during the drought season (five replicates for each site) using clean polyphthalate containers for conducting physicochemical tests and calculating the different parameters related to irrigation. These include sodium adsorption ratio (SAR), residual sodium carbonate (RSC), permeability index (PI), Kelly's ratio (KR), sodium percentage (Na %), magnesium adsorption ratio (MAR), and potential salinity (PS). The mathematical model application evaluated the water quality for irrigation purposes. The results indicated that the qualitative characteristics did not exceed the permissible limits for irrigation. However, a relative increase emerged in the values of electrical conductivity, potential salinity, permeability coefficient, and magnesium adsorption rate, among others, with the river flow in the city. Fortunately, the Tigris River water has better quality for irrigation, and as per the irrigation water quality index (IWQI), the values ranged from 0.3164 to 0.3566.

Keywords: Irrigation water, water quality, Tigris River, water pollution index (WPI), pollution load

Key findings: A relative increase was evident in bicarbonate ions to reach the highest value (2.64 meq.l^{-1}). The Na (%), KR, and SAR measurements (3.99, 0.041, and 0.11, respectively) were necessary to determine the possibility of using water for irrigation.

Communicating Editor: Prof. Ijaz Rasool Noorka

Manuscript received: January 13, 2024; Accepted: April 29, 2024.

Citation: Waffaa Esam Alsinjari (2024). Application of mathematical model to assess the irrigation water quality of the Tigris river in Mosul City, Iraq. *SABRAO J. Breed. Genet.* 56(5): 2175-2183. http://doi.org/10.54910/sabrao2024.56.5.40.

INTRODUCTION

Insufficient safe water resources are one of the most sensitive issues worldwide, with a requirement to deal with it with utmost seriousness for a prominent position on the ladder of global concerns, especially in arid and semi-arid regions, with its connection to human existence, health, development and economy, and vital activities of the organisms and humans (Guasmi *et al.*, 2022; Laluet *et al*., 2023). The absence and limitations of environmental controls on all activities have left behind accelerating ecological problems that may reach critical limits.

Wastewater discharges into the Tigris River and enters Iraqi territory without any treatment, with abuses leading to the dumping of various solid wastes on the riverbanks, causing an imbalance in the aquatic ecosystem (Qaseem *et al*., 2022a). Al-Bahathy *et al*. (2023) noted the proportional decline in the Tigris River water quality throughout Central and Southern Iraq, requiring serious research reconsideration on these issues to develop all necessary conditions to offset and reduce these problems and initiate relevant laws to prevent violations and protect the water resources.

Water shortage is a highly regarded vital pillar of national security, especially in arid and semi-arid areas, where water sources come from neighboring countries. In the future, water scarcity may further develop into an economic and political weapon, increasing tension and the possibility of war. With an increase in water demand in the future, Iraqi land will be bleak due to external challenges, such as dams and irrigation projects built by upstream countries (Al-Mashhadany, 2021). Similarly, traditional irrigation systems and waste in water consumption, which threaten in addition to climate challenges affecting rainfall scarcity and high temperatures, also enhance evaporation and boost the drought problem (Do-Nascimento *et al*., 2024). Recent studies indicated that the Euphrates River water level has decreased by nearly half compared to the past, especially in Central and Southern Iraq, which may not be sufficient to meet the needs of the farming community to irrigate the fields and orchards (Kareem and Alkatib, 2022).

Therefore, implementing efficient management and water resources (surface and groundwater) monitoring is necessary to reduce pollution and waste using modern irrigation techniques. The water quality evaluation can apply the continued qualitative research on water sources, and in emergencies, the water quality index (WQI) weighted mathematical models can help determine the water quality scientifically by selecting the parameters that affect the quality of irrigation water (salinity problems, filtration, and permeability problems, and ionic toxicity). Therefore, it is also necessary to follow the scientific method with accuracy in determining the different parameters affecting the quality index value. All these measurements contribute to a better understanding of water quality by finding a single value that reflects the different overlaps of water quality properties rather than large amounts of data.

The model of water quality index was first an idea by Horton in 1965, then developed by Brown in 1970, and has since been promoted worldwide (Al-Mashhadany, 2023). Overtime, various mathematical models have cropped up, including the National Sanitation Foundation Water Quality Index (NSF WQI), the Oregon Water Quality Index (OWQI), the Delphi WQI, the Canadian Council of Ministers of the Environment (CCME-WQI), and the Water Pollution Index (WPI). Iraq has significantly expanded its use in the past decade, and therefore, several studies have materialized to evaluate the various uses of surface and groundwater and their quality (Al-Saffawi *et al*., 2020, 2021; Najeeb and Saeed, 2022; Younis and Darwesh, 2023). Therefore, the presented study sought to use the pollution index model (PLI) to evaluate the irrigation water of the Tigris River in Mosul, Iraq.

MATERIALS AND METHODS

Study area

In Northern Iraq, the city of Mosul is one of the prime cities with a population of more than 3,729,998 people, according to the statistics of the Ministry of Trade, Iraq, and it rises by 225 masl (CSO, 2018). According to the weather station in Mosul City, about 279 ml of rain fell over the past two decades (Omer, 2023). This area has crop fields and farms spread on both sides of the river, specifically north and south of the study area. With the current city expansion, most wastewater of Mosul City discharge passed through various estuaries dotted along both sides of the river, including the right side (west) (Akab valley and Qara Saray estuary), and the discharge is around 2,090 and 1,793 $m^3.h^{-1}$, respectively (Al-Mashhadany, 2023; Omer, 2023). Meanwhile, on the left side (east), Al-Kharazi and Al-Danfili valleys and Khawsir stream collect wastewater from numerous residential neighborhoods, and their discharges are around 42,129, 9,276, and 5,682 $m^3.h^{-1}$, respectively, which negatively affect the aquatic ecosystem of the Tigris River **(**Al-Mashhadany, 2023).

Methodology

Collecting water samples at six different locations ensued during the dry season (five replications for each location) from the Tigris River since water entered the city of Mosul at the Mushairfa area and passed through the city of Mosul until the heights of Albusief after leaving the city. The sampling used previously washed polyethylene bottles before being filled with simple water several times. The water samples sustained refrigeration in light-proof containers until they arrived at the College of Education's Environmental and Pollution Control Laboratory, University of Mosul (APHA, 2017). **S**ome characteristics of the studied sites using the GPS in Google Earth are available in Table 1 and Figure 1.

Table 1. Characteristics of water sampling sites in the Tigris River, Mosul, Iraq.

Sampling sites	Latitude (E)	Longitude (N)	Usage
1.Mushairefah area	43°04'17"	36°23'39"	For irrigation, livestock watering and civil uses
2. Nineveh forest	43°40'02"	36°22'02"	
3. Fifth Bridge	43°07'43"	36°21'19"	
4. Alhryia Bridge	43°08'41"	36°20'28"	
5. Bosif Heights	43°10'25"	36°18'10"	

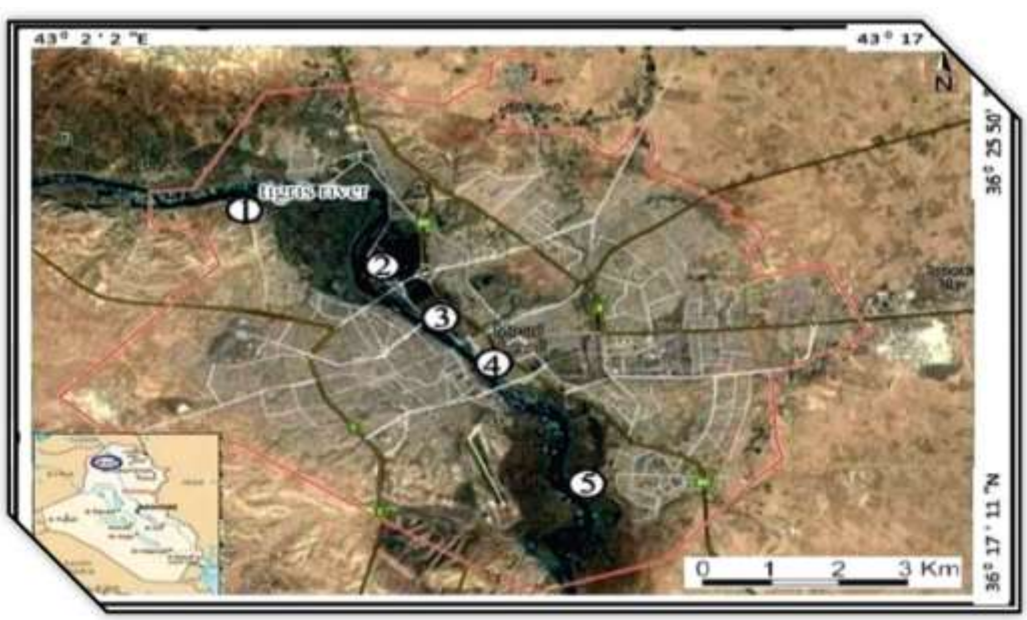

Figure 1. Water sample collection sites from the Tigris River within the city of Mosul.

The acidity function measurement used a pH meter after regulating the device with multiple buffer solutions and an electrical connection EC_{25} with the electrical conductivity device after controlling the device and correcting the temperature. Measuring negative and positive ions followed the globally accepted standard methods (APHA, 2017). The irrigation parameters, i.e., Na (%), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), potential salinity (PS), Kelly's ratio (KR), and permeability index (PI) calculations, employed the following equations (El-Yousfi *et al*., 2022; Bhushan *et al*., 2023; Rahimabadi *et al*., 2023).

$$\text{Na (\%)} = (\text{Na}) \times 100 / (\text{Ca} + \text{Mg} + \text{Na} + \text{K}) \quad .....1$$

$$\text{SAR} = (\text{Na}) / ([\text{Ca} + \text{Mg}]/2)^{1/2} \quad ......2$$

$$\text{PI} = \text{Na} + ([\{\text{HCO}^3\}^{1/2} / \{\text{Ca+Mg+Na}\}] \times 100) \quad ....3$$

$$\text{RSC} = (\text{CO}_3 + \text{HCO}_3) - (\text{Ca} + \text{Mg}) \quad ....4$$

$$\text{PS} = 1/2\text{SO4} + \text{Cl} \quad ....5$$

$$\text{KR} = \text{Na} / [\text{ Ca} + \text{Mg }] \quad ....6$$

All ions used were in $meq.l^{-1}$ units.

Water pollution index (WPI)

The irrigation water quality index (IWQI) is a considerably dynamic process applied to find the interactions among the variables related to irrigation water to get a single value representative of its quality and determine the possibility of using it to irrigate crop fields and orchards. Applying the water pollution index included 11 parameters, i.e., pH, EC_{25}, SAR, Cl, HCO_3, RSC, PI, KR, Na%, MAR, and PS, and also compared with the internationally approved standard limits for irrigation indicated by using the following laws (Calmuc *et al.*, 2020; Khan *et al.*, 2022).

$$\text{WPI} = \frac{1}{n}\sum_{i=1}^{n} \text{PLI}$$

The pollution load (PLi) calculation for the ith parameter used the following equation:

$$\text{PLI} = 1.0 + \frac{\text{Wn} - \text{Sn}}{\text{Sn}}$$

Where Wn: is the measured concentration of the n^{th} parameter and Sn: is the standard limit allowed for the n^{th} parameter. Meanwhile, the formula for calculating PLi differs according to the pH values when the pH value is greater than seven. The Sn*a* represents the maximum allowable pH equal to 8.5, with the following formula applied:

$$\text{PLI} = \frac{\text{Wn} - 7.0}{\text{Sn}a - 7.0}$$

However, when the pH value is less than seven, the Snb represents the minimum allowable pH equal to 6.5, using the following equation:

$$\text{PLI} = \frac{\text{Wn} - 7.0}{\text{Snb} - 7.0}$$

The water condition evaluation depended on the water pollution index with six categories (Khan *et al*., 2022), i.e., WPI ≤ 0.30: Excellent quality (Class I), 0.3 ≤ WPI ≤ 1.0: Good quality (Class II), 1.0 ≤ WPI ≤ 2.0: Moderately polluted (Class III), 2.0 ≤ WPI ≥ 10: Poor quality (Class IV), 4.0 ≤ WPI ≥ 6.0: Very poor quality (Class V), and WPI ≥ 6.0: Unfit (Class VI).

RESULTS AND DISCUSSION

The results indicated that the values of the water pollution index ranged around 3164E-4 and 3566E-4 (Table 2). After classifying for evaluating the water quality for irrigation referred to above, the studied samples of the water category were of good quality (Class II) for irrigation. The same was also the case with bicarbonate ions, which rise relatively with the course of the river to reach the highest value of 2.64 $meq.l^{-1}$ (Table 3). The magnesium adsorption ratio also increased and reached 48.47, as observed at Site 3 (Table 4).

Table 2. Water pollution index (WPI) and pollution load (PLi) of the Tigris River, Mosul, Iraq.

Sites \ Parameters		PIi				
	St. limit	1	2	3	4	5
pH	6.5-8.5	9880 E-4	9800 E-4	9333 E-4	9840 E-4	9747 E-4
EC_{25}	2250	5093 E-4	6027 E-4	7667 E-4	5600 E-4	5920 E-4
HCO_3^{-1}	1.5-85	3160 E-4	3160 E-4	3240 E-4	2960 E-4	3360 E-4
Cl^{-1}	4.0 -10	2633 E-4	0700 E-4	1320 E-4	0990 E-4	0870 E-4
P.S	5.0-7.0	0780 E-4	3217 E-4	4350 E-4	3667 E-4	3650 E-4
Na (%)	60%	0435 E-4	0410 E-4	0410 E-4	0475 E-4	0455 E-4
SAR	18	0038 E-4	0030 E-4	0034 E-4	0034 E-4	0039 E-4
PI	> 75	4013 E-4	4000 E-4	3627 E-4	4480 E-4	3907 E-4
MAR	> 50	8600 E-4	8364 E-4	9000 E-4	8480 E-4	7120 E-4
KR	> 1.0	0270 E-4	0230 E-4	0240 E-4	0230 E-4	0270 E-4
RSC	2.25	0.00000	0.00000	0.00000	0.00000	0.00000
Σ		34802 E-4	35938 E-4	3922 E-4	36394 E-4	35338 E-4
	Values	3164 E-4	3267 E-4	3566 E-4	3309 E-4	3213 E-4
WPI	Status	Good	Good	Good	Good	Good
	Class	II	II	II	II	II

Table 3. The ranges, averages, and standard deviation of the analysis of the Tigris River water in Mosul, Iraq (*meq.l*$^{-1}$ except *Ec in µS. m*$^{-1}$).

Sites \ Parameters		PH	Ec_{25}	Ca^{+2}	Mg^{+2}	Na^{+}	K^{+}	HCO_3	Cl^{-}
1	Mini	6.90	342.60	1.84	0.95	0.080	0.005	0.16	0.37
	Max.	7.65	408.10	2.56	2.07	0.150	0.010	2.56	1.47
	Mean	7.41	381.80	2.09	1.57	1.102	0.007	1.48	0.78
	± Sd	0.26	22.56	0.25	0.32	0.024	0.002	1.00	0.46
2	Mini	6.95	352.40	2.00	1.19	0.060	0.005	0.24	0.16
	Max.	7.60	634.90	2.40	2.00	0.130	0.007	2.88	1.34
	Mean	7.35	452.20	2.24	1.62	0.090	0.006	1.58	0.70
	± Sd	0.23	98.15	0.16	0.26	0.023	0.032	1.01	0.47
3	Mini	6.49	440.50	2.00	1.67	0.100	0.010	0.32	0.64
	Max.	7.30	739.20	2.80	2.15	0.130	0.015	**2.64**	2.42
	Mean	7.00	575.40	2.42	1.97	0.110	0.010	1.62	1.32
	± Sd	0.28	95.41	0.32	0.15	0.010	0.060	1.00	0.70
4	Mini	6.84	370.60	2.08	1.02	0.070	0.006	0.4	0.37
	Max.	7.64	467.10	2.90	2.07	0.130	0.016	2.48	1.74
	Mean	7.38	419.50	2.38	1.64	0.100	0.009	1.48	0.99
	± Sd	0.28	30.80	0.27	0.27	0.021	0.046	0.91	0.53
5	Mini	6.67	411.60	1.92	1.11	0.090	0.007	0.48	0.34
	Max.	7.74	512.50	3.20	1.67	0.130	0.014	2.64	1.47
	Mean	7.31	443.90	2.56	1.40	0.112	0.009	1.68	0.87
	± Sd	0.35	36.30	0.42	0.21	0.016	0.048	0.98	0.44

The Na (%), KR **,**and SAR ratios were the most necessary measurements to determine the possibility of using water for irrigation, which expresses the danger of sodium ions to soil and plants, and they reached 3.99, 0.041, and 0.11, respectively. In irrigation water, the highest concentration of sodium ions breaks down the soil texture and deteriorates its permeability (Table 3). Regarding the electrical conductivity (EC_{25}), the risk of salinity was relatively low in the water of the Tigris River within the city of Mosul, and it fluctuated from 342.6 to 739.2 uS.cm^{-1} (Table 3).

The slight deterioration of the studied water in Mosul city was due to the relative increase in the values of pollution loads (Pli) for PH, EC_{25}, MAR, and HCO_3^{-1}, which amounted to 9880 E-4, 7667 E-4, 9000 E-4, and 3360 E-4, respectively. The pH levels also confirmed these, as shown in Table 3, which also decreased in some periods after entering the city of Mosul to reach 6.49 at the Fifth Bridge (Site 3).

Table 4. The averages and ±Sd for irrigation water parameters of Tigris River water in Mosul, Iraq.

Sites \ Parameters		SO_4^{-2}	P.S	%Na	SAR	RSC	PI	MAR	KR
1	*Mini*	0.72	0.92	2.10	0.540	-4.44	8.55	30.84	0.021
	Max.	2.70	2.21	3.99	0.110	-0.39	43.34	47.57	0.041
	Mean	1.60	1.58	2.71	0.068	-2.06	30.06	42.56	0.027
	± Sd	0.70	0.45	0.65	0.020	1.51	14.41	5.96	0.007
2	*Mini*	1.00	0.9	1.34	0.040	-4.16	10.82	33.14	0.013
	Max.	4.74	2.8	3.48	0.075	-0.77	45.56	47.91	0.036
	Mean	2.58	1.93	2.46	0.054	-2.37	30.03	41.82	0.023
	± Sd	1.38	0.70	0.72	0.012	1.28	14.28	5.410	0.008
3	*Mini*	1.57	1.18	2.18	0.054	-3.99	12.91	40.55	0.020
	Max.	5.16	4.46	3.41	0.077	-0.84	42.76	48.47	0.035
	Mean	3.22	2.61	2.46	0.062	-2.66	27.22	45.02	0.024
	± Sd	1.36	1.19	0.47	0.008	1.19	11.41	3.090	0.005
4	*Mini*	1.32	1.04	1.94	0.040	-4.57	15.05	34.09	0.018
	Max.	3.64	3.56	4.45	0.082	-1.43	43.8	46.8	0.030
	Mean	2.47	2.20	2.85	0.061	-2.61	33.66	40.59	0.023
	± Sd	1.02	0.80	0.86	0.014	1.22	10.10	4.41	0.004
5	*Mini*	1.4	1.36	2.34	0.050	-4.08	11.34	27.27	0.024
	Max.	3.91	3.39	3.03	0.087	-0.37	41.47	46.50	0.030
	Mean	2.65	2.19	2.73	0.071	-2.11	29.25	35.63	0.027
	± Sd	1.09	0.66	0.27	0.012	1.49	13.10	6.850	0.003

The decrease in values due to the effects of sulfur springs near this site containing hydrogen sulfide and the discharge of wastewater from Mosul City containing organic materials decomposed by anaerobic bacteria produced hydrogen sulfide, then oxidized aerobically to form sulfuric acid, as reported in past studies with the following equations (Qaseem *et al.*, 2022a; Omer, 2023):

$$4C_3H_7O_2NS + 8H_2O \rightarrow 4CH_3COOH + 4NH_3 + 4CO_2 + 4H_2S + 8H^+$$

$$H_2S + 3O_2 \rightarrow 2H_2SO_3$$

$$2H_2SO_3 + O_2 \rightarrow 2H_2SO_4$$

Although, mineral acids lower the pH (< 4.5). However, in reality, this did not happen because of the high Acid Neutralization Capacity (ANC) of the Tigris River water, which is rich in carbonate salts in the suspended materials and the bottom sediments of the river. Such type of water also limits the wide fluctuation in values because it behaves like a buffer solution (Al-Saffawi *et al.*, 2020, 2021; Al-Hamdani *et al.*, 2021; Mahmood *et al.*, 2021).

Similar to the above reasons, the concentrations of sulfate and chloride ions rise relatively, reaching rates of 3.22 ± 1.36 and 1.32 ± 0.70 $meq.l^{-1}$ at the exact location. Thus, it reflected an increase in the potential salinity (PS) values, bringing the average to 2.61 ± 1.19 at Site 3 (Table 4). Although potential salinity contributes to soil salinization problems, the values were within the appropriate limits for the irrigation of plants and for all types of soil (Al-Mashhadany, 2023).

The same case was with bicarbonate ions, which soar relatively with the course of the river to reach the highest value (2.64 $meq.l^{-1}$) (Table 3). At the same area, the reaction of formed acids with insoluble carbonates, such as calcium and magnesium carbonate compounds, converts them into dissolved calcium and magnesium bicarbonate ions, as shown in the following equations (Qaseem *et al.*, 2022b; Al-Sallal and Al-Saffawi, 2023).

$$\{CH_2O\} + O_2 \longrightarrow CO_2 + H_2O$$

$$CO_2 + H_2O \longrightarrow H_2CO_3$$

$$CaMgCO_3 + 2H_2CO_3 \longrightarrow Mg(HCO_3)_2 + Ca(HCO_3)_2$$

The magnesium adsorption ratio also rose (48.47) at Site 3 (Table 4). This 4e4 increase was due to the highest magnesium ion concentration (2.15 meq.l^{-1}). Nonetheless, the MAR values were still within the appropriate range for irrigation. Furthermore, all the residual sodium carbonate (RSC) values were negative (-4.57), which hindered the dominance of sodium ions in the soil solution and prevented the deterioration of the permeability and soil texture (Al-Saffawi *et al.*, 2020, 2021).

The measurements of Na (%), KR, and SAR were mainly necessary to determine the possibility of using water for irrigation, which expresses the danger of sodium ions to soil and crop plants. In irrigation water, the highest concentration of sodium ions breaks down the soil texture and deteriorates its permeability. The results also revealed that the water of the Tigris River in the city of Mosul was in the category of low-sodium water (S1) (Table 3), and according to the US Salinity Laboratory, it is safe for use for all types of soil (Al-Mashhadany, 2021; Tekile, 2023). The rates of KR, SAR, Na (%), and PI also fluctuated from 0.027 ± 0.003 to 0.023 ± 0.004, 0.054 ± 0.012 to 0.071 ± 0.012, 2.46 ± 0.47 to 2.85 ± 0.86, and 27.22 ± 11.41 to 33.66 ± 10.109, respectively. All these values were within the standard limits and suitable for irrigation purposes (Al-Hussein, 2023).

Regarding the electrical conductivity (EC_{25}), the salinity risk was relatively low in the water of the Tigris River within the city of Mosul, as it fluctuated from 342.6 to 739.2 uS.cm^{-1} (Table 3). High levels of electrical conductivity due to the discharge of sulfur springs and civil sewage at Site 3 and the quality of the studied water received a good quality (C_2) classification for irrigation purposes, as per the US Salinity Laboratory classification (Al-Hussein, 2023).

The Pearson test showed a significant ($P \le 0.05$) positive correlation between the conductivity values and the respective values of sodium ions, magnesium ions, chloride ions, and the annotated composition (Table 5). Notably, there was a significant ($P \le 0.05$) positive correlation between potential salinity and the ions of calcium and magnesium, and the positive correlation coefficient was much fervent ($P \le 0.01$) with the increase in sulfate ions. It proved correlated to both sodium ions and the pH value. Similarly, a significant correlation appeared between permeability index, pH, and sodium content. Noticeably, a negative correlation emerged between KR and the ions of sulfate and chloride and the MAR. However, the said relationship was significantly ($P \le 0.05$) positive with sodium ions and SAR.

Table 5. Pearson correlation coefficient analysis of the qualitative variables of Tigris River water, Mosul, Iraq.

Parameters	pH	EC_{25}	Ca	Mg	Na	HCO_3	Cl	SO_4	P.S	% Na	SAR	PI	MAR	KR
PH	1.0													
EC_{25}	-0.975	1.0												
Ca	-0.429	0.465	1.0											
Mg	-0.799*	0.788*	-0.046	1.0										
Na	0.394	0.551*	-0.761*	-0.188	1.0									
HCO_3	-0.524	0.568*	0.730*	-0.052	-0.550	1.0								
Cl	-0.873*	0.809*	0.465	0.788*	-0.339	0.220	1.0							
SO_4	-0.804*	0.893**	0.732*	0.544*	-0.862	0.669*	0.685	1.0						
P.S	-0.830*	0.861*	0.776*	0.592*	-0.759*	0.536*	0.860*	0.940**	1.0					
%Na	0.607*	-0.683	0.114	-0.569	0.222	-0.425	-0.190	-0.491	-0.258	1.0				
SAR	0.075	-0.248	0.264	-0.442	0.422	0.203	0.051	-0.304	-0.106	0.530*	1.0			
PI	0.729*	-0.679	-0.155	-0.385	-0.005	-0.679	-0.371	-0.420	-0.327	0.738*	-0.171	1.0		
MAR	-0.465	0.437	-0.540	0.865*	0.226	-0.397	0.429	0.094	0.109	-0.550	-0.500	-0.265	1.0	
KR	0.198	-0.356	-0.015	-0.536	0.612*	0.205	-0.236	-0.485	-0.394	0.309	0.908**	-0.311	-0.434	1.0

*: Significant at $P \le 0.05$, **: Significant at $P \le 0.01$.

CONCLUSIONS

In the city of Mosul, Iraq, the water of the Tigris River proved suitable for irrigation of fields and orchards because the studied parameters, such as Na (%), SAR, RSC, PI, KR, and PS, do not exceed the international standard limits and found suitable for irrigation. It also had a positive impact on the pollutant load (PLi) value. The irrigation water quality index (IWQI) rating received the category of 'irrigation water with good quality.'

ACKNOWLEDGMENTS

The researcher extends her sincere gratitude and thanks to the Presidency of the University of Mosul and the College of Education for Pure Sciences for working in its laboratories and providing all research supplies.

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