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ANNUAL ASSESSMENT OF SELECTED HEAVY METALS (AL, CU, FE, MN) IN THE TIGRIS RIVER WATER AS A MAJOR SUPPLIER OF DRINKING WATER IN AL-DHULUIYA DISTRICT, IRAQ

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Abstract

Background: The ecological and health effects of heavy metals in surface water are severe particularly when the water bodies are used as drinking water supply. The Tigris River, which is a major source of drinking water at the Al-Dhuluiya District, Iraq, is prone to pollution by various types of sources.

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Aim: To determine the changes in the concentrations of aluminium, copper, iron, and manganese at four monitoring stations along the Tigris River.

Materials and Methods: Four sites that had varying environmental and anthropogenic impacts were sampled using water samples that were collected monthly over twelve months (2023-2024). The water samples were analyzed using standard analytical procedures to determine the content of heavy metals. The data were subjected to statistical analysis to determine the spatial and temporal variation.

Results: Aluminium concentrations were recorded between 0.01 to 0.5 mg/L, peaking at Station 1 in August. Copper levels ranged from 0.001 to 0.717 mg/L, with the highest at Station 4 in January. Iron levels were between 0.013 and 0.567 mg/L, notably high at Station 2 in December. Manganese levels reached 0.289 mg/L at Station 2 in January. The results showed that manganese levels in certain samples went above the WHO drinking water limits, while aluminium occasionally exceeded both health and aesthetic guidelines. On the other hand, copper concentrations remained completely below the limits throughout the study period, while iron levels were safely within the permissible international standards during most of the duration.

Statistical analysis revealed significant seasonal and spatial variations attributed to human activities and urban run-offs. Strong positive correlation was found between iron and copper (0.713), while aluminium and copper showed a negative relationship (0.578). These metal variations highlight seasonal operational risks for local water treatment facilities in Al-Dhuluiya District. The temporary increases in manganese and aluminium show that standard treatment protocols need seasonal adjustments to keep the final drinking water safe and prevent potential long-term risks to local residents.

Conclusion: The issue of industrial and agricultural effluents in Al-Dhuluiya District requires constant monitoring, firm control and remedial measures to protect water quality and human health.

Keywords: Tigris River, Heavy metals, Aluminium (Al), Copper (Cu), Iron (Fe), Manganese (Mn), Water quality.

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Introduction

Most freshwater ecosystems are severely becoming practically exposed to heavy metal pollution that tend to pose critical environmental and human health risks. Some of the existing categories of metals that are mostly present in the natural waters are aluminium (Al), copper (Cu), iron (Fe), and manganese (Mn). Their occurrence in the water body is mostly caused by the geological sources and human activities. These processes involve the industrial, agricultural, and the city effluents (Saravanan *et al*., 2024). The elements cannot be biodegraded and, instead, can remain in the ecosystem resulting in bioaccumulation and toxicity of aquatic organisms and people (Zamora-Ledezma *et al*., 2021).

The recent assessments of the world have reported increased levels of the heavy metals on the surface waters in most of the regions. According to Amit *et al*., 2023, the amounts of iron and manganese in most Asian rivers frequently exceed recommended values, emphasizing the necessity of constant monitoring and control. In a recent comprehensive review, Saravanan *et al*., 2024 highlighted the multi-faceted challenges associated with aquatic metal pollution while showcasing advanced remediation techniques and modernized regulatory frameworks.

The Tigris River of Iraq is a significant source of water used in the domestic, agricultural and industrial sectors. But the increase in population and unrestricted dumping of waste materials has caused much concern over the quality of river water. In a study in Mosul, Altahaan and Dobslaw, 2024 reported that there were strong seasonal changes in the concentration of heavy metals and other pollutants, mostly due to the discharge of untreated sewage and infrastructure destruction caused by the conflict. However, the extent and dynamics of this pollution in the smaller urban centres, such as Al-Dhuluiya District, which will be mostly reliant on the Tigris River in their domestic and agricultural operations, are not well researched. In this way, local analysis is significant in identifying the tendencies of water quality and developing the local management practices.

Rather than presenting a routine monitoring dataset, this study aims to evaluate how seasonal metal fluctuations impact the baseline quality of water intakes, thereby providing practical insights for public health safety and the operational

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management of local water treatment plants along the river reach. The results are likely to guide policy makers in coming up with sustainable water resources management policies in the region.

Heavy metal pollution in Iraqi rivers has been documented by several researchers over the years. In the upper parts of the Tigris River near Mosul, domestic waste and war remnants caused significant seasonal changes in pollutants (Al-Ghafoor and Al-Hassany, 2026). Studies in the middle sections of the river around Tikrit and Samarra also noted an accumulation of iron and manganese in water and sediments due to agricultural drainage (Ahmed *et al*., 2025; Saleh *et al*., 2024). In addition, extensive monitoring in Baghdad confirmed heavy metal contamination caused by industrial discharges (Al-Janabi *et al*., 2012). However, there is still very limited information about the detailed monthly variations of heavy metals in smaller, semi-urban agricultural areas like the Al-Dhuluiya District (Al-Sekar and Al-Dabbas, 2022). This part of the river lacks a clear baseline dataset to show how local activities affect water safety. For this reason, the present study was conducted to evaluate the concentrations of Al, Cu, Fe, and Mn over a full year in Al-Dhuluiya, helping to fill this gap and provide useful data for local water management.

Materials and Methods

Study locations

The study locations involved four stations. Station 1 is at the northeast of Al-Dhuluiya District, along which the Tigris River passes after traversing the Al-Mu'tasim subdistrict. The station is located in a low-density agricultural region (34°04′13″ N, 44°10′20″ E). It is the least polluted station of all the examined stations because the river flows rather fast and has the least human impact in this region. Station 2 (34°01′44″ N, 44°12′26″ E) is around 5 km below Station 1, in a peri-urban setting with a lot of crowded settlements, agricultural lands and herds of cattle. The degree of pollution on the site is moderate and this is mainly as a result of mixed land use and low flow of the river as compared to Station 1. Station 3 is situated in the central region of Al-Dhuluiya District (34°01′12″ N, 44°14′12″

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E), being close to highly densified residential areas and working tracts. The location is also exposed to a high level of urban run off as well as agricultural drainage which causes a high degree of anthropogenic pressure on water quality. Station 4 (33°59′58″ N, 44°15′46″ E) is based in a rural and predominantly agricultural region in the southeastern region of Al-Dhuluiya District. The location receives high agricultural overland and intermittent urban runoffs. The river bed is broad and flow is slow, which promotes the accumulation of the debris and the pollutants. These areas of study are depicted in Figure 1.

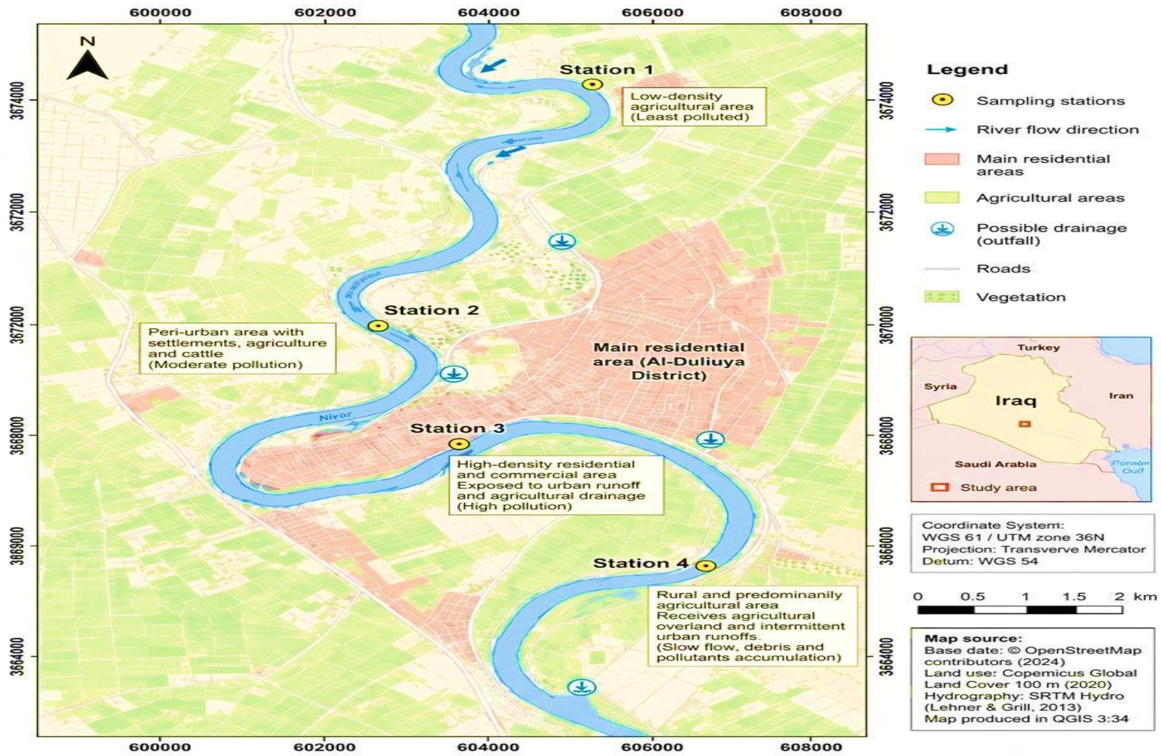

Figure 1: Map of the Tigris River study area within Al-Dhuluiya District

Sampling Design

Surface water samples were collected monthly over a full one-year period from June 2023 to May 2024 at four selected stations. To get representative data, triplicate samples were taken from each site during the first week of every month.

The sampling time was kept fixed between 9:00 AM and 11:00 AM to avoid variations caused by the time of day. Sampling was also delayed for 48 hours if there was heavy rainfall just before the scheduled date, preventing temporary dilution effects. The water was collected from a depth of 20–30 cm using 1-liter high-density polyethylene (HDPE) bottles. These bottles were cleaned in the lab by soaking them in 10% HNO3 for 24 hours and rinsing them several times with deionized water. Right after collection, the samples were acidified to pH < 2 using pure nitric acid to keep the metals from precipitating. They were then stored in ice boxes at 4°C and transferred to the laboratory within three hours for analysis (APHA, 2017).

Preparation of samples and their digestion

Four stations (Figure 1) in the Tigris River of Al-Dhuluiya District were picked to collect water samples. The samples were kept in pre-cleaned polyethylene bottles at 4°C until analyzed. Before the metal analysis, the samples had been subjected to acid digestion to allow all heavy metal ions to be dissolved. A 100 ml aliquot of each water sample was put in a digestion flask; 5 ml of pure concentrated nitric acid (HNO_3) and 2 ml of hydrogen peroxide (H_2O_2) were added to it. The product was heated on a hot plate at 95-100^{o}C within a time of about 1 hour until the mixture became clear and the liquid volume was diminished to about 25 ml. The digested samples were cooled and filtered with Whatman No. 42 filter paper after which they were diluted to final volume of 50 ml with deionized water following the procedure of (APHA, 2017).

Atomic absorption spectrophotometry analysis of heavy metals

The analytes of the selected heavy metals: aluminium, copper, iron, and manganese were analyzed using a flame atomic absorption spectrometer (AAS; model: SHIMADZU AA-6200), in the College of Engineering, Tikrit University, Tikrit, Iraq. All the features were evaluated at their respective resonance wavelengths using the relevant hollow cathode lamp and reference solutions of known concentrations were used to create calibration curves. Blank samples and quality

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control standards were run at the same time as the test samples to assure accuracy and reliability. All the analyses were carried out thrice and the results are in milligrams per litre (mg/L).

Quality Control and Assurance (QA/QC)

To ensure the accuracy of the atomic absorption spectrometer (AAS) data, standard quality procedures were followed. Stock solutions for the target metals (Al, Cu, Fe, and Mn) were obtained from Merck (Germany). Five standard concentrations were used to build the calibration curves, which showed good linearity with R^2 values higher than 0.998. The limit of detection (LOD) was 0.003, 0.001, 0.005, and 0.002 mg/L for Al, Cu, Fe, and Mn, respectively, while the limit of quantification (LOQ) was 0.009, 0.003, 0.015, and 0.006 mg/L. The method was validated using matrix-spiked recovery tests, and the recovery rates ranged between 94.5% and 102.3%. All samples were analyzed in triplicate, and the relative standard deviation (RSD) remained below 5%, confirming the reliability and precision of the testing process (APHA, 2017).

Statistical analysis

Statistical analyses were performed using SPSS software (Version 26.0). The data were first checked for normality and homogeneity of variance using the Shapiro-Wilk and Levene's tests to make sure they met the requirements for parametric analysis. A two-way analysis of variance (ANOVA) was used to study the effects of the sampling months, the stations, and the interaction between month and station. When significant differences were found, Duncan's multiple range test was used as a post-hoc test to compare and separate the means. For all tests, the significance level was set at $P \leq 0.05$.

Results and Discussion

Spatial and seasonal changes in aluminium in the Tigris River

Aluminium is a naturally occurring element in the aquatic ecosystem that is determined by the geochemical conditions and human activities, as well as its

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concentration. The levels of aluminium in this study were 0.01 to 0.5 mg/L with the highest amount detected in Station 1 during the month of August, as indicated in Table 1.

Table 1: Duncan's multiple range test grouping of aluminium concentrations based on month × station interaction

Month	Study location			
	Station 1	Station 2	Station 3	Station 4
June	0.040a	0.020a	0.020a	0.030a
July	0.010a	0.010a	0.030a	0.020a
August	0.500b	0.200b	0.100b	0.020a
September	0.010a	0.170b	0.190b	0.200c
October	0.010a	0.200b	0.150b	0.200c
November	0.010a	0.200b	0.130b	0.200c
December	0.010a	0.200b	0.110b	0.400d
January	0.010a	0.020a	0.010a	0.040a
February	0.010a	0.020a	0.020a	0.140b
March	0.030a	0.010a	0.020a	0.020a
April	0.020a	0.020a	0.150b	0.040a
May	0.010a	0.010a	0.030a	0.020a

Means in the same column with different alphabets are significantly different ($P \leq 0.05$) according to Duncan's multiple range test; Units: mg/L.

There were seasonal variations in the levels of aluminium. During the period between January and May, the level of aluminium was low in all locations. The rise was found to be high beginning in August and reaching its peak in the fall and early winter seasons, especially at Stations 2, 3 and 4. The seasonal increase in aluminium concentrations is likely associated with lower river discharge and higher evaporation rates during the dry season like the low discharge of rivers, the high rate of evaporation and consequent concentration of pollutants, Mechanistically, the distinct autumn peaks at downstream stations (Stations 3 and

4) cannot be solely attributed to atmospheric precipitation. Instead, this anomaly may be highly coupled with sediment desorption dynamics. Under low-flow conditions, aluminum species tend to dissociate from benthic sediments back into the water column, a phenomenon exacerbated by localized pH shifts (APHA, 2017). They are usually intensified by the fact that in late summer and fall, the agricultural and urban runoff increases, adding other inputs that contain aluminium to the river regime (Goher *et al*., 2021). Station 3 had high values all through the year with high values recorded specifically in February, April, August and September, which could be due to the effects of sewage outlets or urban discharges. Conversely, Station 1 had the lowest average concentrations of aluminium all the time due to its upstream position and low exposure to direct sources of pollution.
The U.S. Environmental Protection Agency (USEPA) lists a maximum concentration of aluminium in drinking water of 0.05 mg/L (under aesthetic reasons) and 0.1 mg/L (under health reasons) (Table 6), although the maximum concentration has been increased to 0.2 mg/L under special circumstances by the World Health Organization (WHO). Stations 3 and 4 contain large amounts of aluminium, which exceed the recommended value, particularly during the second half of the year and have to be treated with water suitable to be consumed by human beings (WHO, 2022; USEPA, 2023). It can be explained by the fact that the high levels of aluminium in Station 4 in December and the high levels of aluminium constantly at Station 3 may be due to soil erosion and the resuspension of sediments, which are usually high in the rainy season and during periods of agricultural activity, such as those reported by Khedr and Ghannam, 2025. In addition, the environmental conditions, including pH, turbidity and dissolved organic matter, might increase the movement of aluminium in water (Maphanga *et al*., 2024). Although no single concentrations of aluminium were acutely toxic, a number of sites and samples were detected to exceed the international values of the guideline and they were a health hazard, hence the reason why they have to be continued to be monitored. This is particularly eminent considering the fact that Tigris River is a major source of drinking water among the residents in the immediate environment.

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Multiple range tests as applied by Duncan were to facilitate scientific interpretation at both temporal and spatial scales. Monthly and station-specific analyses were built into this study and demonstrated statistically significant differences in the concentration of aluminium in both sampling months and stations (Goher *et al*., 2021). There were statistical patterns of clustering, which showed that seasonal and spatial differences were neither random nor accidental but aligned with recognized hydrological and anthropogenic processes. This enhances statistical confirmation and supports the tendencies of the field data. The findings also reveal that the pollution of aluminium of the Tigris River not only exhibits seasonal but also spatial variability, which is not only caused by natural processes but also due to human anthropogenic activities, such as agricultural run-off and sewage discharges. One of the recommendations is to use mitigation strategies to curb sources of pollution, as well as protecting drinking water resources. Duncan multiple range test (Table 1) showed that, there were significant changes in the time and the place of aluminium concentrations, especially in the season of the dry season and higher in the downstream location. In addition, Pearson correlation analysis (Table 5) was used to indicate that there was moderate negative correlation between aluminium and copper elements ($r = -0.578$), which indicated that the two elements had different sources of origin, or different mobilization channels in the river ecosystem.

Seasonal and spatial distribution of copper in the Tigris River

Copper is a vital metal that is needed in biological processes of aquatic organisms, as well as humans. Nevertheless, copper may be toxic and lead to serious health problems at high levels of concentration. The results indicated that the copper levels in Tigris River were between 0.001 mg/L to a maximum limit of 0.717 mg/L although the peak was recorded at Station 4 in January (Table 2). Table 2: **Duncan's multiple range test grouping of copper concentrations based on month × station interaction**

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Month	Study location			
	Station 1	**Station 2**	**Station 3**	**Station 4**
June	0.011a	0.070b	0.001a	0.010a
July	0.002a	0.670e	0.002a	0.001a
August	0.001a	0.660e	0.003a	0.020a
September	0.005a	0.003a	0.001a	0.002a
October	0.005a	0.003a	0.001a	0.002a
November	0.006a	0.002a	0.004a	0.001a
December	0.005a	0.003a	0.001a	0.002a
January	0.153b	0.522d	0.289c	0.717e
February	0.111b	0.350c	0.284c	0.470d
March	0.119b	0.320c	0.279c	0.313c
April	0.110b	0.520d	0.102b	0.127b
May	0.001a	0.670e	0.002a	0.027a

Means in the same column with different alphabets are significantly different ($P \leq 0.05$) according to Duncan's multiple range test; Units: mg/L.

The WHO recommends that the maximum drinkable amount of copper in drinking water should be 2.0 mg/L and the USEPA has defined a secondary maximum contaminant level (SMCL) of 1.3 mg/L, taking into account the factors including taste, odour and corrosion of pipes (WHO, 2022; USEPA, 2023). The concentration of copper recorded at all the sampling sites was lower than the international standards, which imply that copper does not pose an immediate health hazard in the area.

The comparatively high allowable concentration of copper relative to that of aluminium (0.2 mg/L, as suggested by WHO) could be explained by the fact that copper is a vital element in human biochemical functions. The variation in the allowable limits is a measure of the different biological functions and toxicological properties of the two metals. Copper is a necessary trace element, being engaged

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in a number of physiological activities, including enzyme activity, erythropoiesis and immunological response. The human body is able to control copper effectively, especially when the amount of intake is kept to moderation. Conversely, aluminium lacks any possible positive effects on human metabolism and has been linked to neurotoxicity, kidney damage and it could be potentially linked to Alzheimer disease when consumed in high amounts (Satarug and Moore, 2024). Thus, health departments have more stringent restrictions on levels of aluminium to reduce health hazards in the long run, whereas the level of copper is somewhat more tolerated by health agencies, because of its critical biological roles.

In the initial months (January to April), there was an increment in copper concentration, especially in Stations 2 and 4. This is explained by the fact that in the rainy season, more runoff takes place, which moves copper remnants of the urban and agricultural activities. The level of mid-range copper in Station 2, which was in a semi-urban location that has livestock and agricultural activity did not change much during the year. Conversely, Station 1 that was not polluted in most months and was upstream had lowest values of copper. The reduction on copper level was significant during May-December and the highest levels of 0.001mg/L at the different points were recorded. The reduction during this season can be attributed to a reduction in the runoff, adsorption of metals to the sediments at the high temperatures and the application of less fertilizer during the late summer (Bravo-Zevallos *et al*., 2024). Mechanistically, this seasonal contrast is further governed by crucial hydrochemical alterations. During the wet months, the surface runoff does not merely transport physical residues, but also introduces high loads of dissolved organic matter (DOM) from agricultural soils; copper possesses a strong chemical affinity to bind with these organic ligands, forming highly soluble complexes that enhance its stability and transport within the water column. In contrast, the sharp decline observed during the warmer months is driven by elevated water temperatures and increased photosynthetic activity of phytoplankton, which naturally raises the water pH. Under these localized alkaline conditions, soluble copper shifts toward chemical precipitation—forming insoluble copper hydroxides and carbonates—which accelerates its adsorption

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onto suspended matter and subsequent settling into the bed sediments (Khedr and Ghannam, 2025). In addition, the fact that the river had a lower flow at Station 4 would be applied to explain the original accumulation of copper but the rise was due to the increased dilution of the river in the high flow months.

Duncan multiple range test (Table 2) indicated that the levels of copper varied significantly over time and location. The statistics were used to compare months with high copper levels and those with minimum levels. Stations 2 and 4 with high concentration levels gave information on the anthropogenic effects and general environmental conditions. A moderate negative correlation was found in Pearson correlation analysis (Table 5) between the two metals (r = -0.578), which may suggest that they could have occurred in the different sources or reacted differently to the hydrological processes (Zhou *et al*., 2023). As a result of this, the copper contents in the Tigris River were not at the acceptable limits in drinking water during the study period. Their variations however are affected by geographical and seasonal factors especially urban and agricultural activities. Such results indicated that special attention to monitoring and controlling pollutants should be paid to local land use and hydrological patterns.

Seasonal and spatial distribution of the iron in the Tigris River

Iron is commonly found in water bodies and it is mostly correlated with the weathering of rocks and sediments and human effects, which include agricultural runoff, wastewater release and corrosion of infrastructure. As the current research revealed, concentrations of iron in the Tigris River were at a minimum of 0.013 mg/L in Station 2 in October and at the maximum at the same station of 0.567 mg/L in December (Table 3).

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Table 3: Duncan's multiple range test grouping of iron concentrations based on month × station interaction

Month	Study location			
	Station 1	Station 2	Station 3	Station 4
June	0.300a	0.300c	0.070a	0.184b
July	0.230a	0.190b	0.060a	0.170b
August	0.238a	0.187b	0.056a	0.220b
September	0.280a	0.043a	0.090a	0.190b
October	0.205a	0.013a	0.051a	0.220b
November	0.235a	0.260c	0.065a	0.430c
December	0.240a	0.567d	0.076a	0.189b
January	0.136a	0.289c	0.194b	0.157b
February	0.167a	0.148b	0.165b	0.171b
March	0.349a	0.296c	0.268b	0.052a
April	0.249a	0.276c	0.243b	0.055a
May	0.238a	0.187b	0.056a	0.107b

Means in the same column with different alphabets are significantly different ($P \leq 0.05$) according to Duncan's multiple range test; Units: mg/L.

The WHO recommends that 0.3 mg/L of iron is the acceptable level of iron in drinking water, which is mostly determined by taste and colour and discolouration considerations, rather than toxicity (WHO, 2022), also, according to the standard classifications, elements like iron and aluminium are regulated primarily based on aesthetic and secondary operational limits rather than direct acute toxicity, impacting parameters such as water taste, discoloration, and treatment facility efficiency (Table 6).

The excesses were recorded at various locations specifically at Stations 2 and 3 towards late autumn and early winter. The findings indicated seasonal changes. Iron levels were moderate in the period between January and May with the highest levels recorded at Levels 1 and 2 at 0.349 mg/L and 0.296 mg/L, respectively. This

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high iron concentration at the onset of the year is probably because of the increased erosion and runoff of the rainy season, which added more iron as a particulate bound to the river (Khan *et al*., 2023). It was determined that concentrations were significantly lowered in July-October in particular in Stations 2 and 3, which exhibited higher temperature, lesser rainfall and heightened sedimentation that might promote the deposition of iron on riverbeds (Haque *et al*., 2019).

Conditions at Station 1 were relatively stable and the high flow rate with little human interference made conditions at Station 1 upstream and the iron concentrations tended to be low. The highest temporal variability was found in Station 2, which was in a mixed-use semi-urban locality with the level of iron being very high in December and way above the WHO limit. This high concentration during December could be related to urban runoff and the possible leaching of iron from old municipal water pipelines (Inayat *et al*., 2024). Station 3 was in a densely populated area with a run-off of agro-business, which indicated moderate levels of iron with occasional spikes. Conversely, Station 4, which was characterized by agricultural activities and low flow had progressive iron accumulation, especially during low flow summer months.

Duncan multiple range test (Table 3) showed that the concentrations of iron in the various stations varied significantly ($p < 0.05$), with a peak of the concentration of iron in Station 2 in December and March, whereas both stations had significantly lower concentration of iron in September and October. Stations 2 and 3 were geographically mixed and had high iron levels, which were very high compared to the relatively constants levels found at Station 1. These results correlate with the effects of land use and hydrology on iron loading. Pearson correlation analysis between the readings of iron and copper levels ($r = 0.713$), revealed that these two metals were strongly and positively correlated (Table 5), which suggests a possibility of co-mobilization or some overlap in common sources of anthropogenic nature, such as urban runoff and irrigation returns, particularly in the middle and southern part of the study area.

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The findings show that the iron content of the River Tigris is seasonal besides being spatially varied and the content is influenced by the precipitation, hydrological and human activities. Even though the majority of concentrations were not higher than the aesthetic guideline limit, there were some exceedances, especially at downstream and urban-proximate locations, which underscores the need to conduct constant water quality monitoring and to maintain water infrastructure.

Seasonal and spatial distribution of manganese of Tigris River

Manganese is a vital trace element that the body needs in minimal quantities to facilitate normal body functions, but over consumption may be detrimental. Elevated manganese concentration has also been linked to neurotoxicity and chronic health conditions in a marine setting, especially among children and infants (Chen *et al.,* 2018). Their activity in fresh water ecosystems is influenced by redox conditions, organic matter and human activities, such as agriculture and discharge of wastewater. As indicated in Table 4, each geographic and time shift was significantly different as indicated by monthly observation of the manganese concentration in the four sites.

Table 4: Duncan's multiple range test grouping of manganese concentrations based on month × station interaction

Month	**Study location**			
	Station 1	Station 2	Station 3	Station 4
June	0.010a	0.020a	0.030a	0.010a
July	0.010a	0.020a	0.030a	0.010a
August	0.090b	0.060a	0.060a	0.002a
September	0.014a	0.006a	0.001a	0.200b
October	0.018a	0.007a	0.029a	0.540d
November	0.014a	0.002a	0.076a	0.120b
December	0.014a	0.006a	0.098a	0.450c
January	0.136b	0.289c	0.194b	0.157b
February	0.167b	0.148b	0.165b	0.171b
March	0.025a	0.036a	0.042a	0.002a
April	0.021a	0.031a	0.022a	0.002a
May	0.230c	0.180b	0.057a	0.100b

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Means in the same column with different alphabets are significantly different ($P \leq 0.05$) according to Duncan's multiple range test; Units: mg/L.

The maximum levels were found at Station 4, reaching its peak in October at 0.540 mg/L, which is likely due to the proximity to agricultural run-offs and peri-urban areas of wastewater discharge. These findings are consistent with the findings of Castro *et al*., 2021 who established that the manganese levels were high in the human-influenced river systems, the pronounced winter elevations and sharp increases in manganese concentrations, especially at Stations 4, highlight the element's strict sensitivity to redox conditions, separating its chemical behavior from other metals. During these colder months, the heavy accumulation of organic waste from densified residential sectors induces localized benthic hypoxia at the river bottom. This lack of oxygen triggers the dissolution of manganese oxides through the chemical reduction of particulate Mn^{+4} into highly soluble Mn^{+2}, thereby accelerating its release from bed sediments into the water column independently of external physical inputs (Chen *et al.,* 2018). The moderate levels found at Stations 1 and 3 were highly varied because of different flow regimes and the sediment dynamics. The manganese levels were also seasonal, as more manganese was recorded during the winter period (between January and May) and thereafter the level was very low during the dry summer months (between June and August). This time series presents the seasonal hydrological processes, including the occurrence of the runoff and the resuspension of the sediment during the months of peak flows that make the rivers more mobile in their metals, such as those reported by Dengg *et al*., 2025.

Moreover, other river systems in the north have studied the surface water, which indicated that the manganese distribution in the water corresponds to the salinity gradient and the flux of organic matter, such as those reported by Kanna *et al*., 2025, which also supports the observed process of the Tigris River.

At some locations and over multiple months, the levels of manganese were more than the WHO guidelines on drinking water (0.1 mg/L), specifically in May at Station 2 and January at Station 1 (WHO, 2022). This casts doubts on the health

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hazards in case such water is used without treatment. The statistical analysis upheld these observations. Duncan multiple range test (Table 4) revealed significant spatial variations, especially between Stations 2 and 4 ($p < 0.05$), showing the difference in the effects of anthropogenic activities on the level of manganese.

Pearson correlation coefficient analysis was performed to identify the correlation of manganese with the other trace contaminating metals, as well as regional and seasonal analysis. The results indicated a positive weak correlation between manganese and copper (r = 0.296; Table 5), which implied that they could have common sources, or otherwise, they could be transported through a similar mechanism, particularly in regions of increased human activity. The relationship between manganese and iron showed a medium negative correlation (r = -0.242) and that could be due to different redox activities or geochemical preferences of various environmental conditions. The relationship between manganese and aluminium was deemed to have insignificant relationships (r = 0.039) possibly that the two metals have weak relationship between their sources or routes of transportation. These statistical relationships mirror the complicated and largely element-specific processes that regulate the activity and distribution of trace metals in river regimes.

Table 5: Pearson correlation matrix

Heavy metal	Heavy metal			
	Al	**Cu**	**Fe**	**Mn**
Al	1.000000	-0.577745	0.083486	0.038851
Cu	-0.577745	1.000000	-0.079824	0.295887
Fe	0.083486	-0.079824	1.000000	-0.241659
Mn	0.038851	0.295887	-0.241659	1.000000

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Table 6: Standard guidelines for the studied metals and their non-compliance status.

Metal	WHO Guideline	USEPA Standard	Type of Standard / Main Concern	Exceedance Status in This Study
Aluminium (Al)	0.1–0.2 mg/L	0.05–0.2 mg/L	Secondary / Aesthetic & Operational (Water color and treatment clogging)	Exceeded in 18.75% of samples, mostly at downstream sites during autumn.
Copper (Cu)	2.0 mg/L	1.3 mg/L	Health-based / Action Level (Gastrointestinal distress / Metallic taste)	Compliant in 100% of samples (0% exceedance rate).
Iron (Fe)	No guideline	0.3 mg/L	Secondary / Aesthetic (Taste, reddish color, and plumbing deposits)	Low exceedance (8.33% of samples), limited to winter at Station 2.
Manganese (Mn)	0.1 mg/L	0.05 mg/L	Health-based & Aesthetic (Neurological considerations / Dark staining)	Highest non-compliance (25.0% of samples), mostly during winter at Stations 2 and 3.

Compliance with Drinking Water Standards

The percentage of samples exceeding the WHO and USEPA limits was calculated to evaluate the overall water quality across the 48 collected samples. Manganese showed the highest rate of non-compliance, exceeding the 0.1 mg/L limit in 25.0% of the total samples, mostly during the winter months at Stations 2 and 3. Aluminium exceeded its health guideline limit (0.1 mg/L) in 18.75% of the samples, mainly during autumn at the downstream stations. Iron showed a low exceedance rate of 8.33%, which was limited to specific winter months at Station 2. On the other hand, copper met the standard in all samples (0% exceedance) throughout the year. These results indicate that manganese and aluminium are the main elements of concern for water management in the study area.

Conclusion

This study demonstrates that heavy metal concentrations in the Tigris River within Al-Dhuluiya District are highly governed by distinct spatio-temporal dynamics

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rather than uniform, year-round pollution. Manganese (Mn) and aluminium (Al) represent the primary elements of environmental and operational concern for local water resource management. Resource management and regulatory monitoring should prioritize Station 2 and Station 3 during the winter season due to elevated manganese levels, alongside downstream reaches (Stations 3 and 4) during autumn owing to temporary aluminium increases. Local water treatment facilities must utilize these seasonal risk windows to proactively adjust chemical coagulation and dosing protocols, ensuring the safety of public drinking water supplies. Ultimately, instead of generic environmental enforcement, regional mitigation strategies should focus on controlling direct agricultural drainage and localized discharges into the river channel during low-flow periods. Consequently, local water authorities should utilize these seasonal profiles to optimize chemical dosing and coagulation processes during high-risk months, ensuring stricter compliance with drinking water standards for the population of Al-Dhuluiya.

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