

Speciation and determination of priority minerals in sediments of terrestrial, riverine, and aquatic environments in the Iraqi river system

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ABSTRACT

Throughout Iraqi rivers, extensive depositional processes have led to the accumulation of significant minerals that threaten aquatic life due to geochemical recycling and the repeated suspension of particles from the benthic habitat into the water column. These minerals can enter the food chain through residue consumption. This study evaluated the impact of certain elements in river sediments using field investigations and contamination indices, including the contamination factor (CF), geo-accumulation index (I_{geo}), enrichment factor (EF), and pollution load index (PLI), followed by statistical analyses. All indices indicate, to varying degrees, severe mineral contamination in the study area. Sediment samples were systematically collected from agricultural zones, river bends and islands, urban areas, and sites upstream and downstream of the Al Hindiyah barrage. The results demonstrate that surface sediments are contaminated with specific minerals particularly Cd, Cu, Ni, Co, Fe, Mn, and Cr exceeding the sediment quality guidelines established by the USEPA. The EF analysis indicates very high enrichment of Cr, extremely high enrichment of Cd and Cu, significant enrichment of Ni, Zn, and Co, and moderate enrichment of Mn across the studied sites. The CF index reveals moderate contamination levels for Pb, Cu, Co, and Cr, while Cd exhibits a very high contamination level. According to the I_{geo} index, the studied sites are moderately to strongly polluted by Cd and moderately contaminated by Cr and Cu. Based on the pollution load index (PLI) for site quality assessment, all sampling sites are classified as unpolluted, except for the site on Um Shuhiaba Island, where baseline levels of certain elements are elevated. Principal component analysis (PCA) and factor analysis (FA) demonstrate that all elements are well represented, accounting for a cumulative total variance of 72.76%. A comprehensive investigation of surface sediment contamination indicates that the sediments pose a hazardous risk to the environment, with emissions primarily originating from anthropogenic sources. This is particularly concerning given the extensive use of the upstream area for drinking water, agriculture, and livestock. Therefore, variations or even opposing effects of environmental management practices on mineral conditions must be carefully considered when assessing the ecological impacts of riverbank management.

Keywords: sediment, Iraqi Rivers, pollution load, index of geo-accumulation, FA, PCA.

INTRODUCTION

Rivers and other water bodies are the most essential natural resources for human life. They provide habitats for different aquatic species and support biodiversity conservation (Hudson, 1993; Valeria, 2003). In water systems, minerals associate with connected sediments containing organic matter, fine sediment particles, iron-manganese and sulphides, hydroxides, and may occur under

alternating sediment conditions, such as variations in dissolved oxygen, temperature, or pH (Dang et al., 2015; Leivuori et al., 2000). Mineral contamination is prevalent in the Iraqi aquatic system, where surface sediments have been identified as the largest reservoirs for hazardous minerals (Abaychi and Douabul, 1985; Hassan et al., 2005; Hassan et al., 2010). The demand for water in Iraq's industrial and agricultural sectors continues to grow to support a population of 45 million

(Al-Taher et al., 2020). The Euphrates and Tigris rivers in Iraq are significant sources for human use, hydropower, irrigation, and water storage, as well as for recharging the groundwater table, purification, and landscape enhancement. Despite this, more than 1.5 billion cubic meters of water are wasted into the Arabian Gulf every year (Al Rabee et al., 2009; Dong, 2003). Rivers transport over 14 billion tons of sediment particles annually. In addition to carrying various waste materials, they also deliver numerous nutrients, particulates, and minerals essential for sustaining the productivity of aquatic ecosystems. More than 85% of minerals entering rivers are deposited in sediments through various processes (Jakimska et al., 2011). Sediments, sourced from both point and diffuse inputs, accumulate on riverbeds and serve as carriers and potential reservoirs for element deposition within the aquatic food chain via biomagnification (Feng et al., 2011; Theofanis et al., 2001). The physicochemical properties of river water vary seasonally (Salomons and Stigliani, 1995; Thuy, 2000). Riverbanks act as critical interfaces for mineral recycling between riparian zones and river water (García et al., 2008). Minerals enter river ecosystems from natural sources and anthropogenic activities, including domestic sewage, industrial operations, agriculture, atmospheric deposition, landfills, and oil contamination (Vane et al., 2020). The minerals pass through three stages: initial dissolution in water, subsequent adsorption, and eventual deposition in sediments, which represent the final accumulation of minerals before being released back into the environment (Feng et al., 2011). When sediments and water are polluted, minerals bioaccumulate in the edible tissues of fish and birds, which in turn endangers human health when consumed (Zoller, 1974; Guan, 2018). Sediments play important role in the adsorption of dissolved minerals (Arora et al., 2008). Mineral contamination is prevalent in Iraqi aquatic systems, where surface sediments have been recognized as the major reservoir for hazardous elements (Abaychi and Douabul, 1985; Hassan et al., 2005; Hassan et al., 2010). Metals tend to accumulate in fine sediment grains bound to organic matter, sulfides, and iron-manganese hydroxides, from which they can remobilize into the water column under varying physicochemical conditions such as changes in temperature, pH, and dissolved oxygen (Leivuori et al., 2000; Dang et al., 2015 ; Al Bayaty and Al Mousawi,2020). While some metals are

essential for aquatic organisms, others like Cd and Pb serve no physiological role and exhibit high toxicity at trace concentrations (Jakimska et al., 2011; Tang et al., 2020). Metals entering rivers from diverse sources adsorb onto suspended particulates, releasing bioavailable ionic forms and soluble complexes for uptake by aquatic biota (Salomons and Förstner, 1984; Zoller, 1974). Prior studies have reported site-specific metal accumulation in river sediments and fish (Al-Tae, 2000; Al-Saadi et al., 1998; Abdulqader et al., 2015). In aquatic organisms, Pb preferentially accumulates in liver and gills, while Cd targets muscles; both invertebrates and vertebrates bioaccumulate Cd, Cu, Pb, and Zn from the river environment (Hellou et al., 1992). Irrigation with polluted water may increase the toxicity of soils and vegetation along riversides. Although numerous geochemical studies on sediments and water in Iraq exist, they primarily reflect the influence of natural factors on sediment mineral concentrations and have not addressed the relationship between anthropogenic contamination and sediment pollution (Al Bayaty, Al Mousawi, 2020). Mineral concentrations in aquatic systems are generally lower in water than in biota and sediments (Al Bassam and Al Mukhtar, 2008; Al-Taher et al., 2020; Salah et al., 2012). Various methodologies have been employed by Iraqi scientists to evaluate the influence of the population on sediments and to calculate factors related to mineral concentrations. Consequently, a comparing and assessing sediment contamination level across different sites is challenging. The primary objectives of this study are to: (i) analyze the distribution of minerals in sediments from the central Euphrates River, an area severely impacted by pollution; (ii) interpret the effects of environmental factors such as sediment constituents, organic matter, and human activities on mineral accumulation to assess contamination levels; and (iii) determine the extent of contamination and identify the key factors affecting water quality. Multivariate statistical techniques, including principal component analysis (PCA) and factor analysis (FA), were utilized to characterize sediment conditions and identify pollution sources. Additionally, several pollution indices were employed to provide a comprehensive assessment of sediment status. The findings can serve as a foundation for developing effective strategies for water resource management and offer rapid solutions to pollution issues.

METHODOLOGY

Geological and hydrological setting of the study area

The Tigris and Euphrates Rivers are the most vital waterways in Iraq, supplying much of the water essential for the development of Mesopotamian society. This study focuses on the water system along the Al Hindiya branch, the main channel of the Euphrates River, which extends 71 km (44 mi) south of the Al Hindiya barrage to the Al Kifil district (Figure 1). Natural factors influencing the Euphrates basin's general direction include the geological setting, the northwest-to-southeast slope, climate conditions, soil characteristics, and vegetation cover. The channel is characterized by shallow depth, considerable width, and gentle sinuosity. It spans from Al Musayyab city, near the northern part of the Al Hindiya barrage (Latitude 32°42'46" N, Longitude 44°15'7" E), downstream to the Al Kifil mouth (Latitude 32°13'27" N, Longitude 44°21'44.2" E). This channel has played a crucial role in the region's socio-economic development. The watershed surrounding the channels relies entirely on river water to fulfill all its water requirements. However, pollutants and wastewater from industrial towns in nearby districts and rural villages enter the main river course. Urban land use, comprising commercial, residential, and infrastructural development, occupies approximately 33% of the catchment area. Additionally, the Hindiyyah main sewage plant discharges directly into the river (Al-Taher et al., 2020).

The areas near the Al Hindiyyah barrage have been impacted by the operation of this structure. These regions feature increased haurs and flooded soils, as well as transitional soils from desert areas that are highly gypsiferous with sandy substrata. The fertility of all soils in the floodplain is relatively high, particularly in terms of nitrogen content. In recent years, the river studied in central Iraq has experienced significant degradation and poor management, resulting in environmental decline.

Sampling locations

The research examined the main locations that have suffered from pollution deterioration. The sampling work was conducted at 14 sites along the stream stretch, with more than 56 samples analyzed near major cities, agricultural regions, islands, bends, or sewage water outlets that

discharge directly into the river and have a serious effect if they enter the river stream directly.

The sediment was tested within the boundaries of Mussiab, Hillah, and Hindiyyah districts, covering the interface area downstream of the Al Hindiyyah barrage up to Al Kifil city. The distance between sites varies depending on obstacles and difficulties in the land topography.

Sampling sites were accurately located using a GPS device to record their coordinates. Some riverbanks, particularly in urban areas, were reinforced with limestone and cement mortar. Figure 1 show the study area and sampling locations, with detailed site information provided in Table 1. Sediment samples were collected for physical and chemical analysis using a handmade device and a boat-operated pump grab sampler constructed from polypropylene bottles, following the protocols of Shelton (1994), APHA (1998), and USEPA (2000). Element concentrations are generally higher during the dry season than in the wet season (Bhuiyan et al., 2011; Salah et al., 2012; Al Bayaty, Al Mousawi), as rainfall and runoff typically dilute these concentrations to standard levels. In this study, sampling was conducted at the end of the rainy season, when minerals are more stable along the riverbanks before being transported by water again. Although mineral levels remained steady during the testing period, their availability may vary with changes in redox conditions, pH, and salinity (Hudson, 1993).

Three samples were collected from the left, middle, and right sides of the river to assess various physical and chemical parameters for evaluating surface sediment quality. Sampling coordinates were kept consistent along the river section to minimize measurement errors. Top-layer scrapes and profiles up to 30 cm deep of alluvial sediments near the riverbanks were obtained, as detailed in Table 1. These sites were selected because they are regularly inundated at the end of the flood season, subjecting them to overbank deposition or effective silting. The collected samples were thoroughly mixed to minimize measurement error and ensure homogeneity for testing.

Samples were placed in polyethylene bags and transported to the laboratory under refrigerated conditions at 4 °C. Testing was conducted in official laboratories under the supervision of specialists from the Iraqi Water Resources and Environment Authority. In the laboratory, the field samples were dried at 104 °C for 24 hours until a constant weight was achieved. Field sediments in

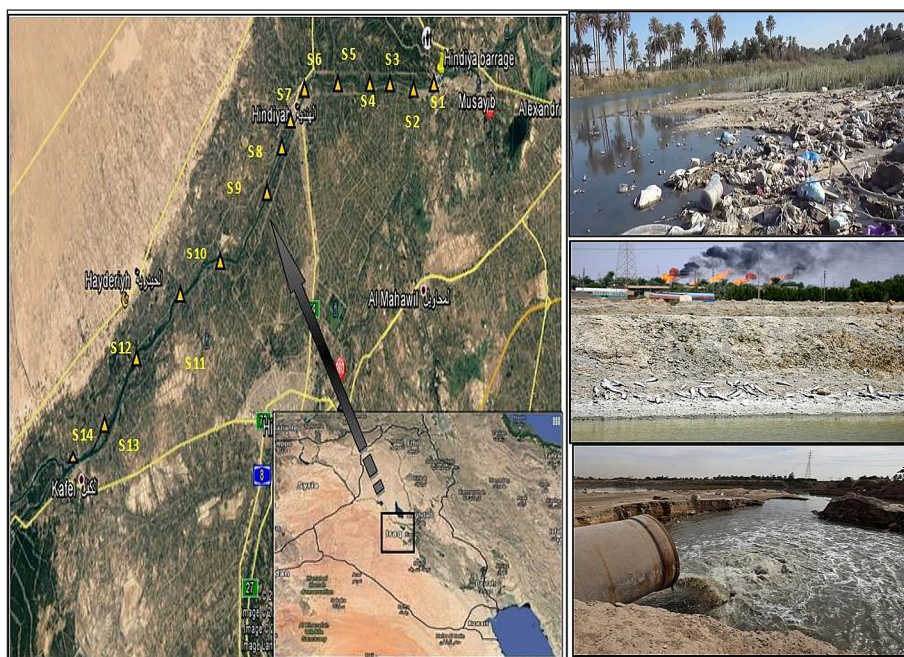


Figure 1. Location of studied sites within Euphrates River stretch; and alarming images of environmental pollution through densely populated areas in the towns where the health and well-being of more than 45,000 residents are at risk of contamination

studied stretch of Euphrates River, are naturally heterogeneous. Using only finer fractions can result in biased assessments if significant portions of the target elements are associated with larger particles. The studied sites influenced by ore-related minerals, specific geological bodies, often exist as coarser debris ($>63 \mu\text{m}$). Using the $<2 \text{ mm}$ fraction allows for more effective geochemical prospecting and delineation of these source bodies for heterogeneity and bias reduction. The sediments contain large amounts of the sand fraction, ranging from $63 \mu\text{m}$ to 2 mm , with most Mn and Fe concretions associated with other geochemical elements (Hudson, 1993). Using the $<2 \text{ mm}$ fraction allows for the analysis of a wider spectrum of grain sizes, from clay/silt to coarse sand, providing a better understanding of the overall (bulk) sediment composition of the study area, including rock debris and various minerals from upstream bedrock.

Particle sizes were determined by sieving sediments through stainless steel mesh with openings smaller than 2 mm until a constant weight was achieved, followed by texture analysis using an agate mortar. Sediment samples with grain sizes smaller than 2.0 mm were selected to capture all chemically active particles and represent local sediment dynamics accurately. These samples were stored in polyethylene bottles for subsequent

digestion and chemical analysis. Texture analysis was performed according to ASTM standards after removing organic material and treating the samples with sodium pyrophosphate to achieve proper chemical and physical dispersion.

The sediment digestion process began by placing 1 g of sediment in a beaker and adding 25 ml of a mixed acid solution composed of hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and nitric acid (HNO_3) in a 3:2:2 ratio. This mixture was subjected to microwave digestion at $70 \text{ }^\circ\text{C}$ for 8 hours with a volume ratio of 10:4 v/v. After digestion, the solution was filtered and diluted to 50 ml using distilled water. The prepared samples were then stored in specialized containers and refrigerated at $4 \text{ }^\circ\text{C}$ until further analysis (Muller, 1981; APHA, 1985).

Concentrations of site minerals iron (Fe), manganese (Mn), zinc (Zn), cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni), and copper (Cu), were determined using an Atomic Absorption Spectrophotometer (AAS) following microwave digestion to quantify mineral content in each sediment sample.

Pollution analytical methods

The contamination in the Iraqi natural environment is a serious concern because it has toxic influence on living organisms and indestructible

Table 1. Details of main diagnosable obstacles and sampling locations **within** the river

Id	Sites	Description	Site at, km	Location	
				Latitude N	Longitude E
S 1	Cement factory	Industrial area	603+00	32° 44' 21"	44° 16' 11"
S 2	Downstream old Al Hindiyah barrage	Rural area and side and Central bar	606+200	32° 42' 45.9"	44° 15' 7.2"
S 3	Downstream New Sadat Al Hindiyah	Rural area and side and Central bar	607+340	32° 42' 40"	44° 25' 59.8"
S 4	Arab Al Mhanawiah village	Rural area with side and Central bar	611+100	32° 40' 16.3"	44° 14' 46.4"
S 5	Al Hindiya Town	Urban area, bend	612+120	32° 38' 42.6"	44° 14' 14.3"
S 6	AL Hamadaniyah project	barren and Rural area	615+410	32° 38' 1.2"	44° 14' 2.3"
S 7	Abu Karbelah villege	Rural area with Side bar	617+150	32° 35' 14.3"	44° 13' 58.3"
S 8	Indian water project	Rural and urban area with side and Central bar	622+430	32° 33' 57.4"	44° 12' 35.5"
S9	Touirij town	Urban area	628+120	32° 32' 09"	44° 11' 39"
S 10	Al Aiyfar village	Rural area side and Central bar	635+230	32° 32' 14.4"	44° 13' 24.3"
S 11	Old Ouffy Gauging Station	Barren area and Side bar	639+020	32° 26' 50.7"	44° 18' 33.0"
S 12	AL kummais village	Rural area Bany Muslim bend	649+060	32° 18' 5.5"	44° 19' 34.9"
S 13	Umm Shuhaybah Island	Barren and Rural area with Central island	657+560	32° 15' 8.8"	44° 21' 26.25"
S 14	Al kifil district	Water treatment plant Central bar	665+120	32° 13' 27.4"	44° 21' 44.2"

Note: *Al Hindiyah barrage at km (605+00) from Iraqi border.

particularly at high level concentrations. Through processes of erosion and deposition, these minerals continue to threaten river life due to their resuspension into the water vertical profile from benthic fauna or from chemical recycling that have accumulated in the riverbed and feed on sediment-cohesion species, leading to transfer through the food chain, including organic elements. Generally, to measure the degree of influence from human activity and industrial processes on the natural parent topography, which increases minerals concentrations in sediments, different indices are used for evaluation as described below:

Index of geo-accumulation

The geo-accumulation index (I_{geo}), introduced by Muller in 1969, serves as a tool to evaluate pollution levels in surface sediments across terrestrial, riverine, and aquatic environments. Mineral contamination in sediments was determined using (Equation 1), which compares current mineral concentrations with pre-industrial levels (Raju et al., 2012):

$$I_{geo} = \log_2 \quad (1)$$

where: C_m represents the measured mineral concentration, while G_m denotes the geochemical background concentration, both in $\text{mg}\cdot\text{kg}^{-1}$ dry mass.

In this study, G_m is considered the reference background concentration of the elements. A factor of 1.5 is applied to G_m to account for natural variations and slight anthropogenic influences. Muller classified the I_{geo} into seven categories, as presented in Table 2. Due to the absence of local background data for sediment minerals at the assessment sites, this study relies on global Earth's crust shale values as reference background concentrations. These values are used to calculate contamination indices for elements in riverine soil, which, as part of the Earth's crust, shares a chemical composition similar to surface shale. This reference is based on Martin and Meybeck (1979), expressed in $\text{mg}\cdot\text{kg}^{-1}$.

Enrichment factor

The enrichment factor (EF) of minerals serves as a valuable index for indicating the type and extent of environmental pollution (Feng et al., 2011). It is widely regarded as the most effective measure for quantifying anthropogenic influence on sediments, as proposed by Zoller (Ravichandran et al., 1995), enabling differentiation between minerals derived from human activities and those from mixed or natural sources (Zhang et al., 2009). The EF is calculated by comparing each value to an established background level, using older deposits formed under similar conditions

Table 2. The Muller classification of seven Geo-accumulation indices (Igeo)

Sediment Igeo	Igeo class	Intensity of contamination
<0	0	Practically uncontaminated
0–1	1	Uncontaminated to moderate
1–2	2	Moderately contaminated
2–3	3	Moderately to strongly contamination
3–4	4	Strongly contamination
4–5	5	Strongly to very strong contamination
>5	6	Very strong contamination

but unaffected by human activity, or based on local or global average compositions (Cato, 1977; Choi et al., 2012).

The EF index normalizes the mineral concentrations at the study site relative to a reference element, such as Fe or Al (Cato, 1977; Chakravarty and Patgiri, 2009). In this study, Fe was selected as the reference element for EF calculation because it is not associated with other site minerals and generally occurs at relatively high concentrations in the Earth’s crust. The EF has been widely applied in research on riverine and marine sediments (Collins et al., 1997; Thair et al., 2014; Salah et al., 2012). The EF is determined using (Equation 2):

$$EF = (Me/ Fe)_{sample} / (Me/ Fe)_{background} \quad (2)$$

where: $(Me/Fe)_{sample}$ represents the concentration ratio of minerals to Fe in the sample of interest, and $(Me/Fe)_{background}$ denotes the natural background ratio of minerals to Fe. In the absence of background data for the minerals, average shale concentration values are used (Martin and Meybeck, 1979). Generally, five classes are distinguished based on the EF (Table 3).

Contamination factor

The contamination factor (CF) is estimated using Müller’s formula, which assesses the enrichment of minerals relative to their background concentrations in sediments. The contamination level is expressed by the CF, calculated as follows (Equation 3):

$$CF = Cm_{Sample} / Gm_{Background} \quad (3)$$

where: Cm_{Sample} is the concentration of the analyzed mineral in river sediment ($mg \cdot kg^{-1}$), and $Gm_{Background}$ is the chemical background concentration ($mg \cdot kg^{-1}$).

The chemical background for minerals was determined based on the global shale background concentration reported by Müller (1981), derived from deeper layers of unpolluted sediments with natural mineral content in the study area. The CF results were used to categorize sediment samples into different contamination levels, as detailed in Table 4.

Pollution load index

The pollution load index (PLI) is calculated using the formula developed by Tomlinson et al. (1980) to assess mineral contamination levels. This index facilitates contamination assessment by enabling comparison between sites, providing a standardized measure for evaluating site quality. According to Angula et al. (1996), the PLI is determined as the concentration factor of each site relative to the global average shale concentration, as reported by Turekian et al. (1961). The formula is presented in Equation 4:

$$PLI = (CF_1 \times CF_2 \times CF_3 \times \dots \times CF_n)^{1/n} \quad (4)$$

where: n represents the number of sampled minerals.

PLI results classify sediment samples as follows: a PLI value less than 1 indicates no pollution; a PLI equal to 1 signifies baseline pollutant levels; and a PLI greater than 1 denotes site quality deterioration (Tomlinson et al., 1980). Specifically, for minerals in the sediments of the river basin, a PLI value ≥ 1 signals the need for

Table 3. Enrichment factor EF categories

Enrichment factor (EF)	Enrichment factor categories
EF<2	Depletion to mineral enrichment
2≤EF<5	Moderate enrichment
5 ≤EF<20	Significant enrichment
20≤EF<40	Very high enrichment
EF>40	Extremely high enrichment

Table 4. Contamination factor CF and level of contamination

Contamination factor (CF)	Contamination level
CF < 1	Low contamination
1 ≤ CF < 3	Moderate contamination
3 ≤ CF < 6	Considerable contamination
CF > 6	Very high contamination

immediate remediation; a PLI between 0.5 and 1 suggests further detailed study is necessary; and a PLI below 0.5 indicates that no significant remediation is required.

Statistical analysis

Multivariate statistical analysis techniques, including PCA and FA, are extensively employed for the purposes of sample identification, classification, and dimensionality reduction (Liu et al., 2003; Filgueiras et al., 2004). In this investigation, PCA and FA were implemented on normalized datasets encompassing 14 variables, yielding the extraction of four factors predicated on eigenvalues. Following the application of PCA, FA serves to further diminish the influence of less significant variables, thereby facilitating a considerable data structure simplification derived from PCA (Menke, 2018).

This simplification is accomplished through the rotation of the axes delineated by PCA according to predetermined criteria, resulting in the formation of new variable sets referred to as varifactors (VFs) (Menke, 2018). This methodological approach enhances the clarity and interpretability of the foundational factors by reducing the impact of less critical variables while augmenting the contribution of highly significant variables to the principal components.

The primary integral rotation yields a new assemblage of factors, each predominantly constituted of a subset of the original variables with minimal interdependence. This procedure effectively categorizes the primary variables into novel, independent classifications (Sharaf et al., 1986). While the main integrals are chiefly linear combinations of observable variables, varifactors may encapsulate inactive, unseen, or hypothetical constructs (Vega et al., 1998). Prior to the execution of PCA and FA, the data underwent standardization via z-score normalization to avert misclassification stemming from variances in magnitude and dissimilarity of numerical values across parameters (Simeonov et al., 2003). Liu et al. (2003) categorized factor loadings into strong, moderate, or weak classifications, corresponding to absolute values of 0.75–0.50, 0.50–0.30, and below 0.30, respectively. Factor analysis was performed utilizing SPSS software to elucidate mineral groupings and, ultimately, to ascertain the sources of integrals within river system sediments (Zhang, 2015).

RESULTS AND DISCUSSION

Soil characteristics

In river basins, soil deposition is classified as “alluvial soil”, which reflects the influence of arid and semi-arid zones in the region. River sediments are affected by various factors, including climate change (e.g., wind, temperature, and rainfall); biological components (e.g., microbes, vegetation, fungi); topography and parent rock type (e.g., mineral composition, texture); and the time period (Hassan et al., 1995). Additionally, human activity plays a significant role, particularly in Iraq, where population dynamics actively impact soil transport from different sedimentation areas for agricultural purposes.

The watershed near the Al Hindiyah Barrage has been influenced by the barrage’s operational system. Sediment accumulation has been observed along riverbanks near the boundary between Al Hilla and Kerbala governorates. The area contains numerous Haura and flooded soils, with fertile floodplain soils exhibiting notably high nitrogen content. Transitional soils from the desert, characterized by high gypsum content and sandy substrata, are also present. Particle size distribution in sediments serves as a valuable tool for determining textural and depositional characteristics, as well as the mineral availability in the parent material (Ali et al., 1987; Mansour et al., 2013; Al Bayaty, Al Mousawi, 2020). Variations in sediment texture indicate sequential processes of erosion and sedimentation, as well as the influence of shell fragments (El Nemar et al., 2011). Various minerals are present in different colors, rather than the typical dark grayish-brown associated with fine river material, likely due to differences in mineralogical composition, as shown in Table 5. The degradation of the Euphrates stream has resulted in soil profile stratification, with layers exhibiting textures ranging from silty clay loam to silty and sandy loam in the substrata. These variations are often linked to differences in mineral composition, clay minerals, structure, consistency, and permeability (Buringh, 1960; Al-Bassam and Al-Mukhtar, 2008). The clay minerals are primarily montmorillonite and some illite, while calcite is a significant mineral in all sediments (ASTM, 1986; Kassim et al., 1997; Bassam and Al-Mukhtar, 2008; UNESCO, 2002).

The sediments contain lime percentages ranging from a minimum of 18.25% in sample S11 to

a maximum of 52.10% in sample S9. Most residue site sediments exhibit lime content between 21.56% and 33.20%, except for samples S1, S2, and S14, which have higher carbonate contents of 45.28%, 42.23%, and 41.35%, respectively, as detailed in Table 5. Lime is a significant component of anthropogenic impact on sediment geochemistry and serves as an indicator of the geological conditions in this region (El Nemr et al., 2013). Additionally, lime content is affected by river flow and the movement of water over the surface of shale. Lower carbonate concentrations are observed at sites directly influenced by water, which is attributed to the recent accumulation of organic carbon that inhibits the decomposition of buried shale particles (El Nemr et al., 2013). This phenomenon also reflects the inverse relationship between mud content and CaCO₃ levels.

Furthermore, the organic matter content (OM%) in sediments results from the decomposition of organisms and dead plants by bacterial action, as well as from soil-derived material transported and deposited over time. The organic matter content is generally low, ranging from 0.31% to 1.44% across all layers. The pH values at all sites range from 6.4 to 7.8, allowing both gypsum and calcite minerals to coexist. Soil pH greatly influences the solubility of nutrients and minerals, with most minerals being highly soluble in acidic or slightly alkaline sediments. A slightly alkaline pH (7.4–7.8) can cause issues with iron availability, whereas sediments with a pH between 6.6 and

7.3 are considered neutral. The cation exchange capacity (CEC) varies from 7.74% to 18.57%, as shown in Table 5. These cations are held negatively by clay particles and organic matter within the sediment layers. Sediments with higher CEC values typically contain greater amounts of clay or organic matter. Therefore, CEC serves as a significant indicator of the limited presence of vegetation roots and rock fragments, reflecting the geochemical characteristics of sediments under the specific geological conditions of this region.

Spatial variation of minerals

Minerals in contaminated environments do not remain in soluble forms for extended periods; they primarily exist bound to organic and mineral substances or as suspended colloids (Chakravarty and Patgiri, 2009). Among the various minerals examined in alluvial sediments, it has been observed that more than seven pipes discharge excess water from land irrigation, groundwater, industrial wastewater, and other agronomic activities into the river from multiple point sources. These sources are the primary cause of varying mineral concentrations at different sites in adjacent areas. Conversely, the low mineral concentrations in some zones may be attributed to their continuous uptake by vegetables cultivated in those regions. The results in Table 6 present the average statistical values for sampling sites compared with sediment quality guideline references.

Table 5. Soil characteristics in sampling sites

Site No.	PH	Texture			O.M %	Lime CaCO ₃ %	*CEC %
		Clay %	Silt %	Sand %			
S 1	7.1	34	52	14	1.28	45.28	17.45
S 2	7.2	36	51	17	1.16	42.23	18.56
S 3	7.8	24	55	14	0.81	33.20	11.45
S 4	7.7	29	62	9	0.98	25.20	10.45
S5	7.2	28	60	12	0.76	27.76	13.67
S6	7.3	23	68	9	1.34	34.22	17.34
S 7	6.5	20	65	15	0.94	28.45	16.78
S8	7.5	15	65	17	0.31	30.32	8.22
S 9	7.8	18	58	24	0.79	52.10	9.29
S10	6.8	12	72	16	1.34	37.60	18.57
S11	7.2	36	51	13	0.43	18.25	7.47
S12	6.4	32	43	25	1.44	18.62	9.53
S13	7.6	20	24	56	0.78	21.56	8.52
S14	7.2	26	44	30	0.94	41.35	15.63

Note: *CEC – cation exchange capacity.

Table 6. Concentration of minerals in the sediments sites during study period

Elements	Max	Min	Mean	±SD	1WHO (SOG)	2USEPA (SQG)	3CCME (SQG)
Pb	37.77	9.84	24.32	9.10	-	40	35.00
Cd	3.23	1.66	2.39	0.44	6	0.6	0.60
Zn	118.95	29.53	86.72	22.57	123	110	123.00
Cu	41.88	20.05	31.02	7.07	25	16	35.70
Ni	55.98	30.22	45.97	8.09	20	16	-
Co	38.34	24.50	29.90	4.11	-	29	-
Fe	3234.54	1903.54	2603.80	373.21	-	30	-
Mn	195.85	83.34	145.91	45.55	-	30	-
Cr	192.73	105.34	152.77	26.15	25	25	37.30

Note: * Values are in (mg/kg); Sediment quality guidelines, referenced as: ¹ WHO (70); ² USEPA (65) CCME (21).

Comparisons with previous studies conducted by various researchers at different times reveal a relative increase in mineral concentrations at some sites, while a decrease is noted at others. Periodic fluctuations are evident, with concentrations peaking as the river enters Iraqi territory and gradually declining until Rawa, completing the first cycle. However, mineral concentrations rise sharply again in Baghdad (Table 7). There is a further reduction in mineral concentrations at Al Mussiab. Sediments are transported from the old mid-formations in the western desert through the Houran Valley during its second cycle. A sudden increase in mineral concentration occurs at Al Kifil, followed by a gradual decline toward Shinafiyah during the third cycle. Relatively acidic rain, driven by the river valley, leads to a rise in the concentration of stable minerals in the sediments (Hassan and Salman, 2010). This phenomenon is attributed to the mineral sources within the rock formations traversed by the river, as well as changes in the erosion system of neighboring areas caused by dam construction in Turkey and

Syria, which affects the river’s sediment load (Table 7). Similarly, comparable mineral concentrations were observed in other river deposits, such as the older sediments of the Anjana formation upstream, where the river valley cuts through this formation. In these ancient sediments, sediment supply is maintained by river-induced erosion (Abdulqader and Kusag, 2015). A recent study assessed potential lead (Pb) contamination in sediments, noting that Pb is highly toxic to animals and humans when it enters the food chain (Zhang et al., 2014). Certain sources, including waste-gas treatment systems and thermal power plants, contribute to increased Pb emissions from operational facilities (Al Mussiab Power Plant). Besides, Pb is the most immobile element, and its content in sediment is closely related to fine clay minerals.

Figure 2a presents the average Pb concentrations at the selected sites, showing minimal variation across locations. Pb levels ranged from 9.835 to 37.77 mg/kg, with a mean of 24.316 mg/kg. Although these values are below the sediment quality guideline of 40 mg/kg (UPES background

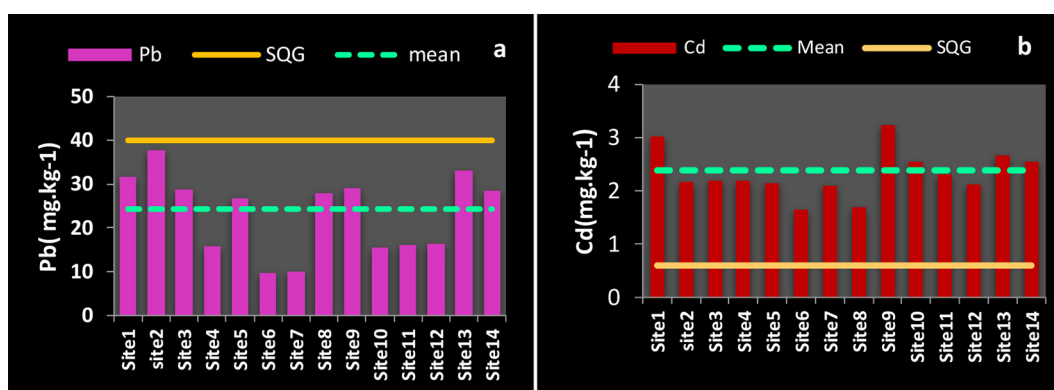


Figure 2. (a) Spatial variation of Pb and (b) Cd concentration in the river

Table 7. Concentrations of minerals in the Euphrates River sediments (mg/kg) in comparison to the other local studies

Sites / Date	Pb	Cd	Zn	Cu	Ni	Co	Fe	Mn	Cr	References
1-Euphrates River (2021)										Muslim et al., (2022)
A-Al Karabla	20	3.5	103	41	203	44	/	/	138	
B- AL Oubaidy	18	4.5	97	28	134	47	/	/	100	
C- Rawa	19	3.8	67	30	156	44	/	/	100	
D-Al Baghdady	22	3.8	94	34	147	44	/	/	101	
E- Heet	19	4.2	73	25	125	41	/	/	88	
F- Al Faluja	17	3.8	92	37	209	50	/	/	127	
G-Al Hillah	19	3.8	82	40	209	50	/	/	127	
H- Al Musiab	19	3.8	188	40	197	50	/	/	124	
I- Al Kifil	17	3.5	79	40	200	53	/	/	128	
J- Al Kufa	19	3	87	38	206	53	/	/	130	
K- Al Shinafiyah	25	3	86	38	200	53	/	/	130	
L- Al Sumawah	20	3.5	86	38	209	53	/	/	140	
2-Euphrates River (2016)										Qamber (2016)
	8.82	0.2	60.5	27.2	175.9	20.3	/	/	82.4	
3-Euphrates River (2010)										Hassan and Salman, (2010)
	39.1	0.37	/	46.6	29.1	/	/	/	303	
4-Euphrates River (2007)										Al-Bassam and Al-Mukhtar, (2008)
	0.59	11.2	67.66	14.14	0.37	8.24	661.7	37.7	0.47	
5-Euphrates River (2001)										Hassan, (2004)
	19.5	3.6	91.16	45.25	182.91	48.6	/	/	119	
6-Euphrates River (1995)										Issa, 1995
	19.5	0.08	30	24.6	125	/	/	450	/	

level), the data indicate contamination of Euphrates River sediments with Pb. Concentrations were lowest at site S6 (9.835 mg/kg) and highest at site S2 (37.77 mg/kg). Elevated Pb levels at S1 (cement factory), S2 (old Hindiyah barrage), S9 (Touraj district sewage water pipe), and S13 (Um Shuhiab island) likely reflect increased human activity in these urban areas.

The average Pb concentration aligns closely with findings by Rabee et al. (2009) but exceeds levels reported by Al Saadi et al. (1998) and Al Bassam (2011) for northern Iraq (upper Euphrates region), as detailed in Table 7. Notably, concentrations at sites S5 and S14 were also recorded. Prolonged exposure to Pb poses significant health risks; thus, the regular use of these sediments for vegetable cultivation by local residents could lead to severe neurological disorders.

The variation of Cd concentration among different sites were illustrated (Figure 2b). The higher value was 3.23 mg/kg at S9 and the lower value was 1.65 mg/kg at S6. The mean value was 2.32 mg/kg, which was greater than the mean shale concentration as background level of 0.2. According to USEPA guideline levels, this stretch of Euphrates River sediments was contaminated by Cd because it exceeded 0.6. The higher concentration of Cd may come from wastewater released from the watershed, enhanced by private industrial factories. Cd is commonly used in ceramics, paint, and plastics, or possibly originates from the (Al Mussiab Power Station) which releases oils with water into the river stream.

High values were recorded at S1, S2, S3, S4, S7, S9, S10, S11, and S12. This may be due to human activities like industrialization, urbanization,

and agricultural runoff, or sequential accumulation of sediment in bends and islands. In other hand, average value of Cd was greater than that evaluated by (Al Saadi et al., 1997; Rabee et al., 2009). It was also higher than the average for World Rivers (Marten and Meybek, 1979) but lower than that reported by (Al Basssam and Al Mukhtar, 2011). Some researchers have discussed that human sources may play a potential character in the feed of Cd in river sediments. These sources result from fertilizers, the discharge of irrigation water into river water, and primarily the discharge of untreated municipal wastewater from sources of highly populated cities directly into the river stream. Numerous landfill areas are spread around the river stream.

A Zn mineral is a very readily mobile element. Therefore, sources of Zn are connected with practices of agricultural and non-ferrous elements industry (Pendias, 2000); Abanuz, 2011). Maximum concentrations of Zn have carcinogenic and toxic impacts, resulting in neurological and hematological issues, hypertension, complications, and disorders of kidney and liver functions (Roa, 2001). The Zn minerals concentration ranged between a low value of 29.525 mg/kg at site S8 and high value of 118.945 mg/kg at site S9 (Figure 3a). These values were lower than the mean world shale concentration considered as background level. The mean value of zinc Zn concentration as 86.724 mg/kg was below the USEPA guideline of 110 mg/kg, as illustrated in Figure 3a. Most sites were below the sediment quality guidelines (SQG) level except for S9 and S13. This is due to the effect of sewage water discharge from many outfall pipes of Touwiraj city. Additionally, the series of deposition processes over time could have increased this element at site S13. Generally, these values

indicate that the river stretch sediments were uncontaminated by Zn.

Also, Copper Cu is widespread in the river environment almost Cu composite IS available found in water, soil, sediment, rock and air are strongly fixed to dirt and dust or embedded in minerals. It is deliver into the river system by industries and is often established near industrial landfill areas, settings, and waste disposal sites (Raju, 2012).

Copper Cu joins the river system through natural sources domestic, waste dumps, wastewater, phosphate and fertilizers, (e.g dust carried by windblown from native soils and decaying vegetation). Consequently, It can be strongly connected to organic matters and inorganic materials like sand clay in the surface layers of sediments and may not transfer very far once delivered.

Copper (Cu) mineral concentrations were found to range from a low of 20 mg/kg at site S3 to a high of 41.87 mg/kg at site S13. These values exceed the mean shale background concentration of 11.2 mg/kg. Furthermore, the mean concentration surpasses the USEPA sediment quality guideline of 16 mg/kg, indicating that river sediments contain approximately twice the recommended pollution level for Cu according to sediment quality guidelines (SQG).

In document presented by Al-Bassam and Al-Mukhtar (2008), they explained that Cu concentrations at several sites in the Euphrates basin that were higher than those recorded in this study. The mean value of Cu was also lower than the global average for rivers. A high variation in Cu concentration was observed among sites. In (Figure 3b), the sites S4, S6, S7, S12, S13, and S14 have Cu concentrations higher than the mean value 31.024 mg/kg, while other sites show lower values, as illustrated in (Figure 3b). In general, all

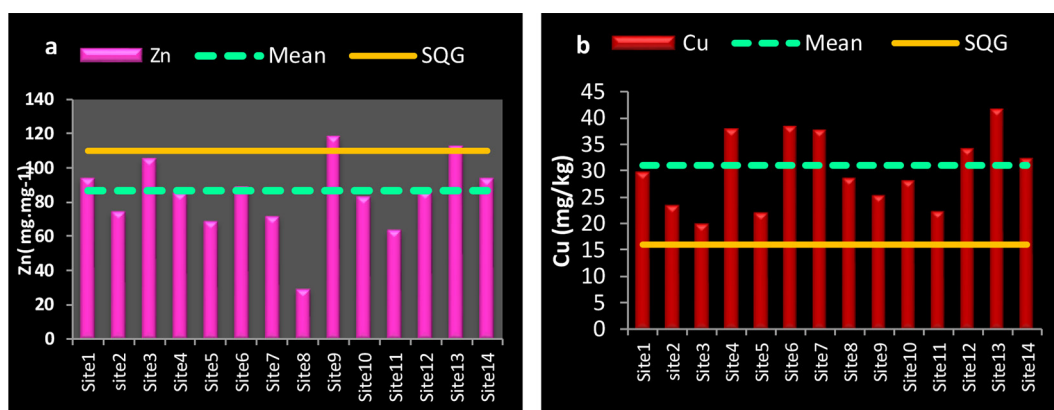


Figure 3. (a) Spatial variation of Zn; and (b) Cu distribution in the river stretch

sites showed levels higher than the SQG threshold of 16 mg/kg. Elevated concentrations were found near population centers and agricultural areas. When copper compounds enter water bodies, dissolved copper may exist as free ions, copper compounds, or, more commonly, copper bound to suspended particles. Soluble copper compounds, which are frequently used in agriculture, are readily absorbed by plants and animals and pose greater health risks.

The investigation also reveals that nickel (Ni) is a naturally occurring mineral, abundant and widely distributed in the soil crust. Major sources of Ni in sediments include inadequately treated wastewater from processing industries. Its concentration reflects both soil-forming processes and contamination (Kabata-Pendias and Pendias, 1992; McGrath, 1995). Ni concentrations range from 30.215 mg/kg at S12 to 55.98 mg/kg at S7, with an average of 45.972 mg/kg, which is significantly higher than the SQG level referenced by the USEPA, as shown in Figure 4a.

High concentrations were also reported at sites S2, S4, S10, and S13 causes of the transport of Ni with stream water and deposition points. Significant sources of Ni are weakly treated wastewater discharged from private processing industries.

The differences in the concentration and availability of Ni among study sites are attributed to the higher specific adsorption of organic particles, which can limit the absorption of minerals sites by plants. Lime, fertilizer, sewage sludge, and industrial waste are the primary sources of nickel in sediment deposits (McIlveen and Negusanti, 1994). pH is the main factor influencing nickel solubility, sorption, and mobility, whereas iron-manganese mineral clay content and soil organic matter play a minor role but may gain importance

with the decreased use of soil liming in agriculture (Benko, 1983; Cempel and Nikel, 2006; Raju et al., 2012). In general, distribution of Ni in the sediment layers is uniform. Additionally, Nickel is common in urban areas due to typical accumulation from a series of depositions through anthropogenic activities.

The samples showed the highest concentration of cobalt (Co) at site S13, measuring 38.34 mg/kg, followed by S7 and S1 with 34.68 mg/kg and 34.385 mg/kg, respectively. Site S12, located at a bend, and recorded a high concentration of 31.845 mg/kg, while site S2 exhibited a notable level of 24.5 mg/kg. Other sites displayed similar values, with an average concentration of 29.89 mg/kg. The spatial variation of Co concentration is illustrated in Figure 4b. According to USEPA guidelines, no reference level is available for comparison.

The predominant form of iron (Fe) is observed to be associated with carbonate fragments, either adsorbed onto grain surfaces or, more plausibly, substituting calcium within the calcite matrix (Beltagy, 1984). The concentrations of Fe exhibited variability, ranging from 1903.54 mg/kg at site S6 to 3234.54 mg/kg at site S10, yielding a mean concentration of 2603.804 mg/kg. This average Fe concentration surpasses the sediment quality guideline of 30 mg/kg established by the USEPA. The discrepancies in Fe concentration across the various sampling locations are illustrated in Figure 5.

The elevated levels of Fe within the sediment are attributed to protracted industrial activities, encompassing machine tool fabrication, pigment synthesis, and effluent discharges from the Al Mussiab Electrical Power Station, which directly released oil-contaminated water into the river, consequently facilitating the transport of

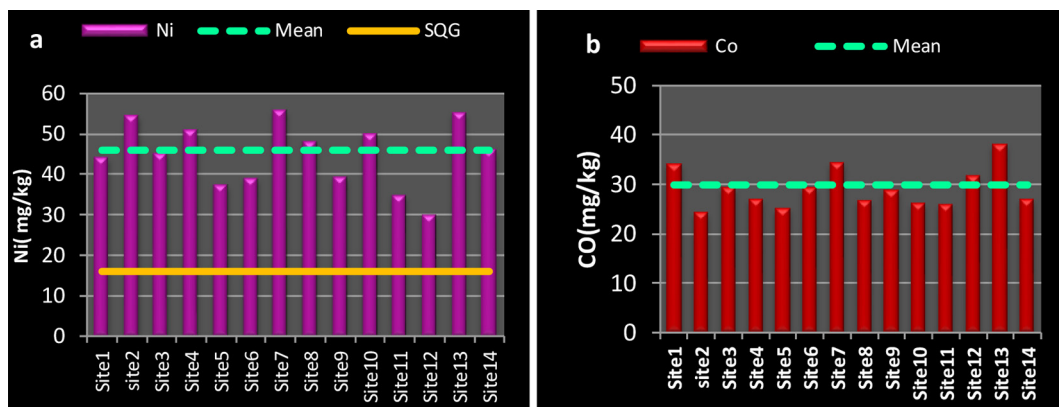


Figure 4. (a) Spatial variation of Ni; and (b) Co distribution in the river stretch

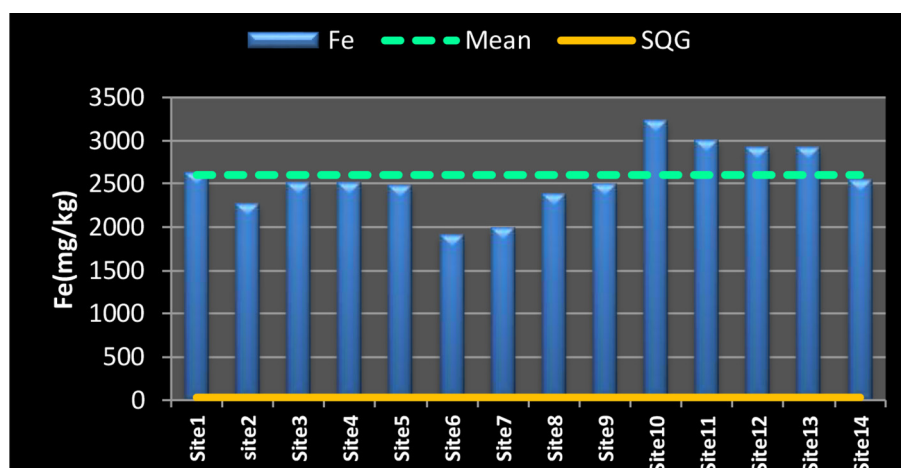


Figure 5. The variation of Fe minerals along study river section

pollutants to the sediment matrix. The highest recorded Fe concentrations and their resultant variability have also been documented by additional scholars (Hassan et al., 2010; Salah et al., 2012). The manganese (Mn) concentration within the sediments of the investigated sites varies from 83.34 mg/kg at S8 to 195.85 mg/kg at S2 (located downstream of the antiquated barrage). The average Mn concentration is recorded at 145.912 mg/kg, which exceeds the USEPA sediment quality guideline of 30 mg/kg, as depicted in Figure 6a. All sampling locations display elevated Mn concentrations, which can be ascribed to the substantial mud content present in sediment accumulation. Manganese is recognized as a vital element for both fauna and flora, occurring naturally at approximately 0.1% within the Earth's crust (NAS, 1973). While a deficiency in Mn can lead to physiological anomalies in mammals, there exists no substantiated evidence to suggest its carcinogenic potential (Sivaperumal et al., 2007).

The maximum value of Cr was observed at S2, and the minimum concentration was determined at S5 (Touuiraje township area), with a range of 105.34 mg/kg to 192.725 mg/kg respectively, and a mean value of 152.773 mg/kg. Additionally, higher values of Cr were observed at S13 (Island Umm Shuhiaba) and S14 (Al Kifil City), with about 173.905 mg/kg and 178.983 mg/kg respectively. There are meaningful variation in Cr levels in the sediments of S1 and sites S2 and S3 compared with other downstream sites, as illustrated in (Figure 6b).

The increase of Cr content in sediment is attributed to industrial wastes such as municipal, electro sludge, oil wastes, sewage sludge, etc. The

pollution of Cr from various sources is controlled by redox potential and soil pH. At the study sites, high concentration values of minerals are related to the excess quantity of water input directly into the river stream from many drainage pipes in surrounding areas.

It is also observed that some minerals (e.g., Mn, Cr, and Fe) are unevenly distributed along the study sites. These minerals are showed higher concentrations that may probably originate from mechanical and chemical processing, construction materials, rubber industry, soldering and welding flux; plastics, lubricants, pharmaceuticals, waste from burns, and ointments from medical centres.

The low mineral concentrations at some sites may result from continuous removal through dredging or uptake by vegetation in designated riparian areas. Compared to USEPA classifications, average concentrations of minerals such as Cd, Cu, Ni, Fe, Mn, and Cr are relatively high, whereas Pb and Zn generally show the lowest concentrations, and Co levels are near the guideline threshold. Overall, the origin of rocks and their presence in the river system has contributed by a major role in increasing the concentration of certain minerals in river sediments. Besides prevailing climatic conditions, which have also played an important role in changing the effects of these minerals – whose stability varies under different weather conditions – the distance of transport also plays a similar role in this area. It has been noticed that river bends play a major role in changing the concentration of some minerals, in addition to the relationship between particle size in river sediments and the concentration of minerals.

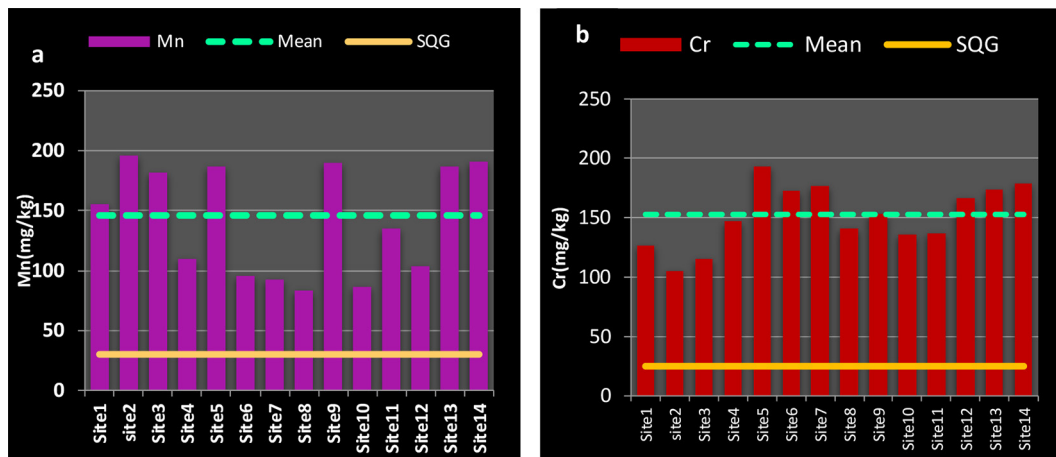


Figure 6. (a) Spatial variation of Mn; and (b) Cr distribution in the river stretch

Aquatic ecosystems are affected by the increased concentration of some minerals through rain runoff and excess flushing from anthropogenic activities, and natural sources involving industrial and domestic sewage, landfills, agricultural activities, oil pollution, and atmospheric deposits. The sediments act as sinks for these minerals through several processes: first dissolved in water, then adsorbed, and finally accumulated on the riverbed. Also, because of site-specific rainfall, dissolved minerals are flushed from the surface layer of soil out from the watershed areas, then settle in vast floodplain zones, and finally join the riverbanks to reach the water flow

In Iraq, it is common to recycle most river sediment materials from the river channel into the adjoining vast watershed or floodplains, where many types of vegetation are grown in polluted soils. In addition, the irrigation water may be polluted with site minerals (Abaychi and Douabul, 1985; Hassan et al., 2010 Salah et al., 2012). Therefore, this process will produce polluted crops. Consequently, long-term consumption of polluted food grown in the region might create severe toxicological impacts for consumers.

Degree of contamination, and pollution load

The assessment of general sediment contamination in the studied river reach is based on the EF, CF, and PLI indices, as detailed in Tables 8, 9, and 10. EF values indicate extremely high enrichment for Cd, Cu, Cr, and Pb, in descending order, while Co, Zn, and Ni show significant enrichment. The EF for Pb in Euphrates sediments ranges from 11.18 to 38.76, with values exceeding 20 at sampling sites S1, S2, S3, S5,

S8, S9, S13, and S14 (Table 8), classifying these sites as very highly enriched in Pb. CF values for Pb range from 0.491 to 1.888, averaging 1.167 (Table 9). Most sites exhibit CF values between 1 and 3, indicating moderate Pb contamination, except for S4, S6, S7, S10, S11, and S12, where values are below 1, indicating low contamination.

EF values for Cd in the river sediments range from 113.782 to 207.631, with all sites exceeding 40, categorizing the Euphrates sediment as extremely highly enriched (Table 8). CF values for Cd vary between 5.516 and 10.767, with a mean of 7.75 (Table 9). All sampling sites fall into the very high contamination category ($CF > 6$), except for S6 and S8, which are classified as very high and considerable contamination, respectively. The EF values for most sites, concerning both Zn and Ni concentrations, range from over 5 to under 20, indicating significant enrichment for these metals (Table 8). However, the majority of sampling sites S3, S6, and S9 exhibit EF values exceeding 20 for Zn, classifying them as “very high enrichment” sites. These locations are situated in or near townships or villages. The CF values for Zn vary from 0.3107 to 1.252, with a mean of 0.888 (Table 9). Sites with CF values below 1 for Zn and Ni are considered to have low contamination, while S3, S9, and S13 show moderate contamination with CF values above 1. Exposure to Ni through the food chain may lead to health issues such as lung injury, nasal sinusitis, skin allergies, rhinitis, and nasal mucosal damage (Tomlinson et al., 1980).

For Cu, EF values at all sampling sites exceed 40, classifying the river sediments as “extremely high enrichment,” except at sites S3, S5, and S10, which are categorized as “very high enrichment.”

CF values for Cu range from 1 to 3 at sites S1, S2, S3, S5, S8, S10, S11, and S14, indicating moderate contamination. In contrast, sites S4, S6, S7, S9, S10, and S13 exhibit considerable contamination.

Table 8 shows that the EF values for cobalt (Co) range from 13.088 at site S10 to 28.070 at site S7. Most sites exhibit EF values between 5 and 20, indicating “significant enrichment,” except for sites S1, S6, S7, and S13, where values exceed 20, reflecting “very high enrichment” according to Mmolawa et al. (2011). The contamination factor (CF) values for Co at sites S1, S3, S6, S12, and S13 range from “low contamination” to “moderate contamination.»

Regarding manganese (Mn), Table 8 indicates that EF values at most sampling sites fall between 2 and 5, corresponding to “moderate enrichment.” Sites S8, S10, and S12 have EF values below 2, classifying their sediments as exhibiting “deficiency to minimal enrichment.” As shown in Table 9, CF values for Mn range from a minimum of 0.0980 at S8 to a maximum of 0.23 at S2. Since all CF values are below 1, the sediments throughout the studied river stretch are considered to have low contamination by Mn.

Evaluation of chromium (Cr): The EF values for Cr range from 21.828 at site S8 to 47.235 at site S6. Sites S1, S2, S3, S4, S8, S9, S10, S11, S12, S13, and S14 exhibit EF values between 20 and 40, classifying them as having “very high enrichment.” In contrast, sites S5, S6, and S7 have EF values exceeding 40, indicating “extremely high enrichment” of Cr.

All studied sites show CF values between 1 and 3 ($1 \leq CF < 3$), corresponding to a “moderate level of contamination” for Cr.

Furthermore, the PLI was employed to assess sediment contamination at the sampling sites. Most sites have PLI values below 1, indicating no overall pollution, except for site S13, where the PLI exceeds 1. This suggests deterioration in site quality at S13. The relatively high PLI at S13 (Umm Shuhiaba Island), a wetland partially covered with vegetation formed through sequential deposition over thousands of years, may explain this observation. Several studies report that wetland species tend to accumulate higher mineral concentrations in their roots or belowground parts than in aerial parts (Karpiscak et al., 2001; Stoltz and Greger, 2002). Consequently, mineral concentrations in sediments have increased in this wetland area, likely due to partial sedimentation (see Table 10).

Index of geoaccumulation Igeo

It is essential to distinguish between natural background levels and anthropogenic inputs; therefore, the human impact on mineral concentrations in sediment sites was assessed using the Igeo index. Generally, Igeo comprises seven grades or classes (Table 2). For Pb, most sampling sites exhibited Igeo values below 0 (Table 11), indicating they are practically uncontaminated according to Muller’s classification, except for sites S1, S2, and S13, where values were below 1, classifying them as unpolluted to moderately polluted.

Table 8. Enrichment ratio ER values of sites sediments

Sites	Pb	Cd	Zn	Cu	Ni	Co	Mn	Cr
S1	28.086	184.163	17.594	47.385	11.603	21.035	3.244	25.130
S2	38.764	153.825	16.293	43.406	16.697	17.411	4.749	24.213
S3	26.560	139.195	20.740	33.209	12.462	18.826	3.976	23.880
S4	14.617	139.355	16.733	62.751	14.024	17.260	2.391	30.259
S5	25.092	137.927	13.674	37.289	10.441	16.417	4.127	40.464
S6	12.016	139.332	23.159	84.525	14.219	25.011	2.750	47.235
S7	11.666	168.759	17.847	79.105	19.406	28.071	2.561	46.401
S8	27.110	113.782	6.092	50.143	13.986	18.037	1.918	30.772
S9	27.062	207.632	23.503	42.352	10.895	18.729	4.180	32.035
S10	11.180	125.845	12.759	36.359	10.717	13.088	1.469	21.828
S11	12.345	123.431	10.533	30.969	7.981	13.906	2.461	23.799
S12	12.947	115.726	14.535	48.853	7.115	17.509	1.947	29.561
S13	26.477	146.598	19.129	59.778	13.088	21.152	3.521	31.032
S14	25.933	161.028	18.327	53.174	12.596	17.131	4.115	36.661

Table 9. Contamination factor CF for the sites sediments

Site	Pb	Cd	Zn	Cu	Ni	Co	Fe	Mn	Cr
S1	1.590	10.084	0.990	2.673	0.651	1.186	0.056	0.183	1.411
S2	1.889	7.250	0.789	2.108	0.807	0.845	0.049	0.230	1.170
S3	1.437	7.283	1.115	1.790	0.668	1.014	0.054	0.214	1.282
S4	0.793	7.317	0.903	3.394	0.755	0.933	0.054	0.129	1.629
S5	1.338	7.117	0.725	1.982	0.552	0.872	0.053	0.219	2.141
S6	0.492	5.517	0.942	3.448	0.577	1.019	0.041	0.112	1.918
S7	0.499	6.983	0.759	3.372	0.823	1.196	0.043	0.109	1.969
S8	1.392	5.650	0.311	2.565	0.712	0.922	0.051	0.098	1.567
S9	1.451	10.767	1.252	2.263	0.579	1.000	0.053	0.223	1.704
S10	0.778	8.467	0.882	2.520	0.739	0.907	0.069	0.102	1.506
S11	0.798	7.717	0.677	1.995	0.512	0.895	0.064	0.158	1.526
S12	0.815	7.050	0.910	3.066	0.444	1.098	0.063	0.122	1.847
S13	1.662	8.900	1.193	3.739	0.815	1.322	0.063	0.220	1.932
S14	1.418	8.517	0.996	2.897	0.683	0.933	0.054	0.224	1.989

Table 10. The PLI index for sites sediment

Site	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
PLI	0.921	0.839	0.842	0.807	0.820	0.712	0.758	0.686	0.931	0.780	0.733	0.785	1.072	0.934

Analysis revealed moderate to strong Cd contamination, with Igeo values ranging from 2 to 3. Sites S6 and S8 exhibited moderate contamination ($1 < I_{geo} < 2$) according to Müller's classification. Cd exposure can lead to anosmia, renal dysfunction, anemia, hypertension, and cardiovascular diseases (Wang et al., 2010). Igeo values for Zn and Ni at all sites were below 0, indicating low pollution levels for these metals in river sediments. Cu showed site-specific variation: sites S1, S2, S3, S5, S6, S7, S8, S9, S10, and S14 had Igeo values between 0 and 1 (uncontaminated to moderately contaminated), while the remaining sites fell in class 1 ($I_{geo} = 1-2$; moderately contaminated) per Müller's classification.

Igeo values for Co, Fe, and Mn were negative (< 0) at all sites (Table 11), indicating no pollution by these elements in Euphrates sediments between Al Hindiyah Barrage and Al Kifl city. For Cr, sites S1–S3 showed negative Igeo values (unpolluted), while sites S4–S14 had values in class 1 ($0 < I_{geo} \leq 1$; uncontaminated to moderately contaminated).

Overall, the mean geo-accumulation index for all elements was negative (Table 11), confirming that average concentrations in this river stretch are below global shale baseline levels.

Statistical analysis

Based on the statistical analysis, four variation factors (VFs) were identified in this study: Varifactor 1 (VF1), with an eigenvalue of 6.093, accounts for 42.24% of the total variance and shows strong positive loadings on Fe, Ni, Co, and Mn, as well as moderate loadings on Cu and Cd (Table 12). Varifactor 2 (VF2), with an eigenvalue of 1.959, explains 13.03% of the variance and exhibits strong to moderate loadings. Varifactor 3 (VF3), with an eigenvalue of 1.17, accounts for 8.3% of the variance, displaying strong loading for Zn and moderate loading for Pb. Varifactor 4 (VF4), with an eigenvalue of 1.153, explains 7.2% of the variance, with strong loading for Cr and moderate loading for Mo. Together, these four VFs represent all evaluated elements and explain a cumulative total variance of 72.76% (Table 12). VF1 is predominantly composed of Fe, Cu, Co, Ni, Mn, and Cd, which are mainly linked to anthropogenic sources. The mineral trends from site 5 to site 9 correspond to areas of intense urbanization and industrialization within the studied river basin. These metropolitan regions contribute to contamination through agricultural runoff, industrial discharges, and untreated urban effluents.

Table 11. Representation of Igeo of minerals at different sites and diagram of Igeo of minerals at different sites

Sites	Pb	Cd	Zn	Cu	Ni	Co	Fe	Mn	Cr
S1	●		*	●	*	*	*	*	*
S2	●		*	●	*	*	*	*	*
S3	*		*	●	*	*	*	*	*
S4	*		*		*	*	*	*	●
S5	*		*	●	*	*	*	*	●
S6	*		*		*	*	*	*	●
S7	*		*		*	*	*	*	●
S8	*		*	●	*	*	*	*	●
S9	*		*	●	*	*	*	*	●
S10	*		*	●	*	*	*	*	●
S11	*		*	●	*	*	*	*	●
S12	*		*		*	*	*	*	●
S13	●		*		*	*	*	*	●
S14	*		*	●	*	*	*	*	●
Legend									
*	Igeo<0			Uncontaminated					
●	0 < Igeo ≤ 1			Uncontaminated / moderately contaminated					
	1 < Igeo < 2			Moderately contaminated					
	2 < Igeo < 3			Moderately / strongly contaminated					
	3 < Igeo < 4			Strongly contaminated					
	4 < Igeo < 5			Strongly / extremely contaminated					

Copper (Cu) and nickel (Ni) are commonly released from fuel combustion and industrial emissions, with primary human sources including fuel combustion, mineral mining, and processing. Manganese (Mn) originates from anthropogenic activities such as sewage sludge application, refining, fertilizer use, atmospheric deposition,

and waste incineration, all prevalent in this river stretch. Iron (Fe) in sediment samples frequently correlates strongly with cadmium (Cd), reflecting their similar classification in this study, as both often derive from industrial effluents. Varifactor VF2 emphasizes the influence of water’s physical properties, as these measurable parameters appear

Table 12. Loadings of experimental variables on principal components for sediment samples, including extraction and rotation methods

Element	VF1	VF2	VF3	VF4
PH	0.293	0.529	0.173	-0.02
Pb	-0.157	-0.431	0.703	-0.27
Cd	0.583	0.419	0.213	-0.51
Zn	0.293	0.069	0.873	-0.01
Cu	0.683	0.219	0.373	-0.01
Ni	0.873	0.089	0.053	0.1
Co	0.813	-0.161	0.103	-0.06
Fe	0.903	0.089	0.113	0.04
Mn	0.773	0.079	-0.137	0.11
Cr	0.163	0.029	0.013	0.65
Eigenvalue	6.093	1.959	1.153	0.91
% of Variance	42.24	13.03	7.2	6.71
Cumulative %	42.16	56.61	64.93	72.76

interrelated. VF3 is linked to minerals such as lead (Pb) and zinc (Zn), originating from urban runoff. Elevated levels of these minerals were notably detected at sites S5 and S10, consistent with discharges from private factories and welding workshops. Varifactor VF4 is primarily associated with chromium (Cr), likely from agricultural sources, since fertilizers can contain several hundred to thousands of parts per million of chromium.

CONCLUSIONS

This treatise provides a comprehensive analysis of contamination levels in sediments from terrestrial, riverine, and aquatic environments within the Iraqi river system. The findings reveal that pollution is unevenly distributed, with significant contamination at specific locations. Pollution indices indicate that the elevated mineral concentrations in the sediments pose a serious environmental hazard. Enrichment factor distinguishes between natural and anthropogenic sources of minerals by comparing a target metal to a conservative reference element (like iron). PLI provides a simple, site-specific index that can be used to compare the overall contamination of different sites. The study area is heavily impacted by emissions primarily from anthropogenic sources, with agricultural activities identified as the main contributors to contamination in adjacent regions. Overall, the high mineral concentrations in the sediments likely result from groundwater mixing through leaching or originate from human activities, including uncontrolled solid waste disposal and untreated or inadequately treated liquid effluents from unauthorized industrial facilities. Statistical analysis revealed that most elements, including Cu, Co, Ni, Mn, Fe, Zn, and Pb, originate primarily from anthropogenic sources, particularly industrial and residential activities. In contrast, chromium is likely derived from agricultural sources, such as fertilizers. Variations in mineral concentrations at different sites can be attributed to factors such as granule shape and size, as well as the river's morphology at measurement locations. Additionally, sedimentary rocks in the desert valleys of the Upper Euphrates within Iraqi territory contribute seasonally to increased mineral concentrations in the river. These minerals are transported by rainwater runoff from the Huran valley, which flows into the Euphrates River north of Baghdad, where the oldest geological formations exert significant

influence. The sand-structured compositions of Al Dabdba and Anjana play a crucial role in sediment processing within the Euphrates water system. Furthermore, some sediment deposits may originate from neighboring regions, such as the Anatolian Plateau in Turkey and Syrian territories, as the river transports elements through erosion and deposition processes. Pollution was not evenly distributed along the river. Some sites, being less industrialized and sparsely populated, receive relatively lower pollution inputs. Additionally, certain areas benefit from the river's natural self-purification and assimilative capacity due to strong water flow. To control sediment contamination, legislative measures must prohibit the discharge of untreated or inadequately treated industrial effluents into the Euphrates River. Moreover, regular monitoring of toxic minerals along the riverbanks is essential to assess environmental quality, and prompt remediation efforts should be implemented to address existing mineral pollution.

In over all sediment pollution in the Euphrates River, rich in heavy metals (like Cr, Cd, Ni, Pb) and organic matter from agricultural, industrial, and sewage runoff leading to severe Iraqi health crises, including high rates of skin digestive issues (diarrhea, cholera), diseases, kidney/respiratory problems and liver disease and increased cancer risks, as people drink polluted water and use contaminated water for irrigation, causing systemic illness and affecting both humans and livestock.

Correlate specific contaminant levels with known health effects using existing epidemiological and toxicological evidence. The results are compared against established safety thresholds, regulatory standards, and epidemiological data. This is done by identify specific contaminants and their concentrations, understand exposure pathways, and assess potential toxicological effects on local ecosystems and human populations. The process involves both ecological risk assessment and human health risk assessment using a multi-exposure approach. Determine how the local population and ecosystem elements come into contact with the contaminants. Primary pathways for humans include breathing contaminated particulate matter, volatile organic compounds). Consuming contaminated drinking water, food (e.g., contaminated fish, crops grown in polluted soil), or accidentally ingesting contaminated soil/dust (especially relevant for children). Dermal contact and direct contact with contaminated soil or water. Identify vulnerable populations such as

certain groups (children, pregnant women, the elderly, individuals with pre-existing conditions, low-income communities) are often more susceptible to environmental hazards and may have higher exposure levels. For assess ecosystem effects by evaluate impacts on local flora and fauna. Contaminants can impair growth, reproduction, and behavior in wildlife, altering predator-prey interactions and overall ecosystem function. Sediment pollution in the Euphrates River, rich in heavy metals (like Cr,Cd, Ni, Pb) and organic matter from agricultural, industrial, and sewage runoff leading to severe Iraqi health crises, including high rates of skin digestive issues (diarrhea, cholera), diseases, kidney/respiratory problems and liver disease and increased cancer risks, as people drink polluted water and use contaminated water for irrigation, causing systemic illness and affecting both humans and livestock.

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