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Assessment of Heavy Metal Contamination in Water, Sediments, and Agricultural Soils in Iraq: Environmental Risk and Implications for Human Health

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Abstract

Water sources in Iraq, including the Tigris, Euphrates, the Shatt al-Arab estuary, and Mesopotamian marshes, together with soils used for agriculture irrigated by these waters, suffer from an increased load of heavy metals that has been widely described in recent scientific papers. This review covers recent literature, mostly from 2021 to 2026, regarding the presence of heavy metal contamination in three environmental compartments in Iraq, namely, surface water, sediments, and agricultural soils. Concentrations of cadmium, lead, chromium, nickel, iron, manganese, zinc, copper, arsenic, and mercury are assessed according to pollution and ecological risk indices used in reviewed studies, such as contamination factor, geo-accumulation index, enrichment factor, pollution load index, Nemerow index, ecological risk index, metal index, and pollution index. Among all studied locations, namely, Baghdad, Mosul, Basra, Erbil, Duhok, Kirkuk, Fallujah, and the southern phosphate belt, cadmium and lead are identified as the metals with the highest concentration and anthropogenic origin, associated with urban, industrial, oil, and post-war sites. Human health risks reveal exceeding non-carcinogenic and carcinogenic thresholds, with children as the most vulnerable population group. This review is composed of five sections and offers some recommendations concerning sewage treatment, effluent regulation, site cleanup, and monitoring.

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Keywords: Heavy metals, water pollution, sediment contamination, agricultural soils

1. Introduction

The freshwater resources, food production capacity, and a considerable part of the country's industry depend on one hydrologic system: the Tigris and Euphrates Rivers that join to form Shatt al-Arab and then discharge into the Arabian Gulf. The same system supports the Mesopotamian Marshes, once one of the largest wetlands of the Middle East. During the last four decades, the same hydrologic system and soils have become the recipient of environmental stress caused by rapid urbanization, the development of industrial and oil sectors, lack of treatment of municipal waste, and wars.

Metals constitute one of the persistent pollutants in such a situation. Unlike many organic pollutants, metals (cadmium, lead, chromium, arsenic, etc.) do not degrade but accumulate in sediments and soils, are transferred to crops and aquatic organisms and finally enter the food chain and affect humans. Several of these substances are considered proven human carcinogens according to toxicology reviews (arsenic and cadmium especially), while lead, chromium, and mercury can cause neurological, renal, hepatic, and developmental disorders with no known safe exposure level ^[1].

There are two features that make the Iraqi case unique in the context of pollution research as opposed to other settings. First, the Iraqi oil sector is one of the direct sources of environmental pollution. During wars, Iraqi refineries and pipelines become the target of attacks, as well as the result of gas flaring and old facilities. The local population in Basra has raised concerns about the increasing rate of cancer, contaminated water and soil in connection with nearby oil facilities ^[2]. The second feature of the

situation in Iraq is the "conflict pollution", the pollution associated with damaged industries, military waste, and unexploded ordnance. This type of environmental pollution is being researched as a separate problem and is highlighted in successive institutional assessments of the situation in the country^[3, 4]. Nevertheless, the usual sources of heavy metal pollution – untreated sewage, industrial effluents, and wastewater irrigation are also mentioned in the country's environment^[1].

The current primary studies show the extent of the problem: a 2026 assessment of water from Tigris River in Baghdad revealed that Metal Index values exceeded the safety threshold everywhere in both dry and wet periods^[5], a post-conflict assessment of Mosul water showed the cumulative Hazard Index values exceeding 200-300 for drinking water from the same river^[6, 7]. In 2026, a geo-environmental assessment of soils and water near an actively working phosphate mine in Southern Iraq revealed "very high ecological risk" according to the Potential Ecological Risk Index^[8].

This review examines three main questions that are directly relevant to the environmental management and public health policy of Iraq: (i) the current state of heavy metal pollution in surface water, sediments, and agricultural or urban soils in the country's basins and cities; (ii) the level and possible sources of such pollution as indicated by standardized pollution and ecological risk indices; and (iii) the human health risk associated with such pollution. Section 2 describes the search and synthesis methods of this review; Section 3 reports the synthesis results divided by environmental compartment and risk indicators; Section 4 discusses the results' patterns, health implications, limitations, and recommendations. The conclusion is provided in Section 5.

2. Method

2.1. Literature Search Strategy

The current review employs a narrative and scoping synthesis methodology, which is appropriate given the extensive nature and multi-compartment/policy-oriented focus of the literature available on heavy metals in Iraq. Literature was obtained using keyword-based searches on academic databases and publisher platforms, such as Google Scholar, PubMed and PMC, ScienceDirect, SpringerLink, Wiley Online Library, MDPI journals, IWA Publishing, and IOPscience. The searches were supplemented with institutional/technical reports from UNEP, ReliefWeb, the Conflict and Environment Observatory, and Human Rights Watch, which report on environmental pollution due to conflict. Searches included combinations of the keywords "heavy metal" or "heavy metals," or individual element names (Cd, Pb, Cr, Ni, As, Hg, Fe, Mn, Zn, and Cu), with "Iraq" and with "water", "river", "sediment," or "soil," or with names of important geographic regions (Baghdad, Mosul,

Basra, Shatt al Arab, Erbil, Duhok, Kirkuk, Fallujah, and Ramadi). Additional keywords related to pollution, ecological risk and human health risk indices included "contamination factor," "geoaccumulation index," "enrichment factor," "pollution load index," "Nemerow index," "potential ecological risk index," "hazard quotient," "hazard index," and "incremental lifetime cancer risk."

2.2. Inclusion and Exclusion Criteria

Literature was selected if it reported field measurements of heavy metal concentrations in surface water, sediments, or agricultural and urban soils in Iraq and used any of the pollution, ecological risk, or human health risk indices. The time span of the search is limited to publications from 2021 to 2026 to obtain up-to-date information on the environmental conditions in Iraq. Several studies from before the period (2017-2020) have been included due to their importance as baselines and methods used in other studies^[9, 10, 11, 12], and they are marked as such when cited. Studies without data from Iraq, studies dealing only with non-metal pollutants, and opinion papers without any primary measurements have been excluded. Only a few studies from outside Iraq were used as sources for methodology and human health risk index calculations and are marked as such.

2.3. Synthesis Approach

Out of more than 140 sources, which were found through several dozen searches, those that are relevant to Iraq have been selected. Out of these sources, 42 have been chosen for citations, including 38 studies reporting field data from Iraq during the years 2021-2026 and four baseline studies/general toxicology studies, which set the stage of the problem and give some historical perspective. The selected literature is grouped according to the environmental compartment (surface water, sediments, and agricultural/urban soils) and synthesized narratively by each compartment and by geographic region. Second-pass synthesis, regardless of the environmental compartment, is done by comparing pollution, ecological, and human health risk indices among the selected studies. A formal quality score is not calculated; instead, the highest priority is given to reproducible results obtained by independent research groups.

2.4. Analytical Framework

The findings are organized in a source-pathway-receptor framework (Fig. 1): the sources and pathways of anthropogenic and conflict-related pollution release metals into three environmental compartments; pollution and ecological risk indices assess the contamination severity in each compartment; and human health risk indices translate the compartment-level contamination into exposure and risk models.

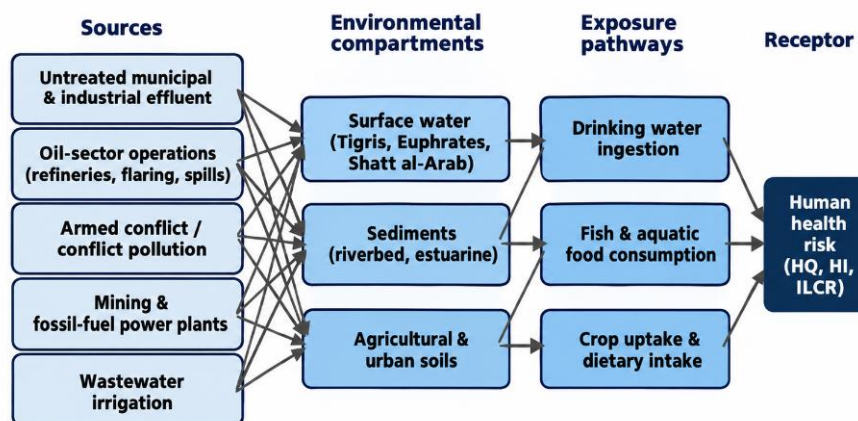


Fig 1: The source-pathway-receptor approach employed to arrange the synthesis, whereby the driving forces are arranged according to the compartments and the exposure routes.

3. Results

3.1. Sources and Drivers of Heavy Metal Contamination

According to the literature, the heavy metal pollution in Iraq comes from point source discharges, diffuse agricultural and urban inputs, as well as disturbances associated with conflict. In the river-system research done in Baghdad, Basra, and Mosul, it turns out that inadequate sewage treatment allows untreated industrial and municipal effluents to end up being discharged into the rivers or washed into them due to runoff, which is associated with industrial, residential, and agricultural sources, but not with geological background according to the principal component and factor analysis [9]. Moreover, the oil industry in Iraq is one of the main sources of soil, surface water, and groundwater pollution in the southern part of the country, including wastewater discharges from refineries into the Shatt al-Basra canal and complaints of contaminated water and degraded soil in the area of expansion of the oil industry in Basra [2]. The other way, related to armed conflicts, gives the specific pollution pathway to Iraq: several assessments of the Tigris River and the soils in the adjacent areas after the war in Mosul show an increase in the concentration of cadmium and lead due to the bombing of industrial facilities and the breakdown of environmental control in 2013–2017 [6, 7], with the analogous processes described in national post-conflict assessments [3]. Controlled explosive minefield clearance has proven to be another local source of heavy metals: soils in and around the demining pits in Halgurd-Sakran National Park in Iraqi Kurdistan showed a significant increase in the concentrations of nickel, chromium, manganese, cobalt, and copper following the controlled detonation [12]. Mining and heavy industry are also suspected: phosphate mining in southern Iraq has been associated with land degradation and heavy metal contamination of the soils and adjacent surface waters, with cadmium and lead being the dominant contaminants [8], fly ash and residues from burning fossil fuel in the power plants in central and southern Iraq have been linked to increased concentrations of chromium, nickel, cobalt, cadmium, zinc, lead, and copper in the adjacent soils [13]. Moreover, wastewater irrigation has been documented as an

agricultural pathway: municipal wastewater application on vegetable crops in Erbil has led to an increase in metal concentrations in soils and plant tissues [14].

3.2. Surface Water

As was found from assessments of Tigris River water quality, there is significant heterogeneity in space and time. In Baghdad, a 2026 assessment of the Metal Index (MI) across three stations revealed MI ranging from 5.8 to 12.22 in the dry season and 5.78 to 12.22 in the wet season, with all the values exceeding the limit of unsuitability for any use; the most persistent exceedance was of lead (0.092–0.191 mg/L) followed by chromium and iron as consequences of industrial effluent and sewage discharge [5]. As another assessment of Tigris River in 2024 combining various pollution indicators and health-risk model showed pollution gradient along the whole river [15]; a similar 2024 assessment of the Al-Tarmiya stretch in northern Baghdad used Pollution Index, Metal Index, Contamination Factor, and Potential Ecological Risk Index for lead, zinc, cadmium, nickel, and aluminum and found slight-to-moderate levels of lead and aluminum [16]. A separate 2024 CCME Water Quality Index assessment of the Tigris in Baghdad City generally characterized standard physicochemical parameters as fair-to-good despite metal-specific indices revealing more serious pollution [17].

In Mosul, the analysis of CCME Water Quality Index and the Heavy Metal Pollution Index showed the exceedance of the limits set by World Health Organization (WHO) for cadmium, lead, chromium, and nickel at most of the monitoring sites, with the maximum contamination in the central urban area influenced by military activities in 2016–2017; hazard quotients for cadmium and lead exceeded the safety limit ($HQ > 1$) at each site, with cumulative hazard index having extremely high levels – higher than 300 in 2022 and higher than 200 in 2023 [6]. Another 2024 study attributed seasonal-independent exceedance of the WHO limits for cadmium, lead, chromium, and nickel in water and sediments to the direct effect of war-related ammunition and sulfur-field ignition and destroyed wastewater infrastructure [7].

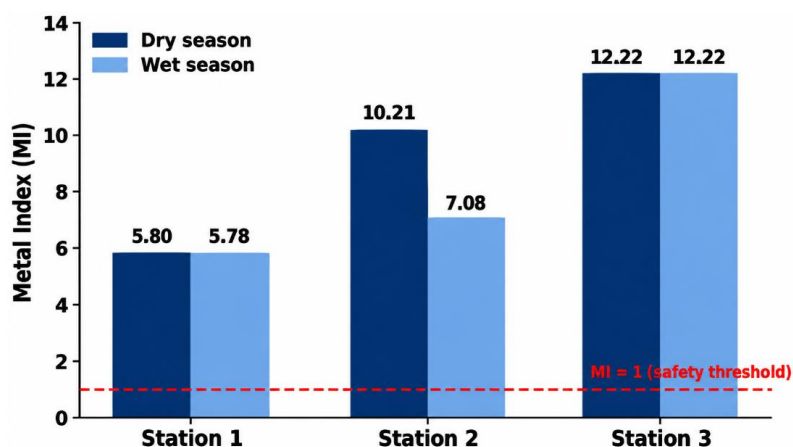


Fig 2: Metal Index (MI) of Tigris River water at three Baghdad monitoring stations, by season. All stations exceed the MI = 1 safety threshold in both seasons [5].

On the other hand, in 2023, research using the Canadian and pollution water quality indices in the southern part of the Tigris indicated improved water quality in certain years [9]. A study on water and sediment quality around Baghdad revealed minimal levels of heavy metals in the river and low pollution load in the sediments, indicating that contamination in the Tigris River is confined to locations with industrial outfalls, densely populated cities, and areas affected by conflicts.

Concerning the Euphrates River, comparative analysis of water quality of Tigris and Shatt al-Arab in 2022 identified common pressures from urbanization and agricultural activity [18]. Studies conducted in Anbar province, including water quality indices of tap water in Ramadi [38], reported contamination levels that are likely to have implications for growth and development, organ damage, and neurotoxicity because of constant untreated discharge. Investigations into sediment contamination between Heet and Fallujah have

utilized the potential ecological risk index for the metals Cd, Cr, Cu, Ni, Pb, and Zn in sediment profiles [19]. Additionally, microbial contamination of the Euphrates River in Al-Hilla was reported, indicating common contamination of the river by both metals and microorganisms [20].

Shatt al-Arab, which is the confluence of the Tigris and Euphrates and the main water resource for Basra, was the location where the worst contamination cases were reported in the reviewed literature. The surface water in the area close to south Iraqi phosphate mining exceeded the World Health Organization drinking water guidelines for Pb (38.5 µg/L), Cd (4.85 µg/L), and As (22.5 µg/L), with non-carcinogenic hazard index in children up to 16.39 at specific sites and carcinogenic risk index due to exposure to hexavalent Cr and As exceeding the 10^{-6} threshold [8]. In 2025, another research into seasonal and spatial variations in the middle Shatt al-Arab also identified anthropogenic pressure on water quality.

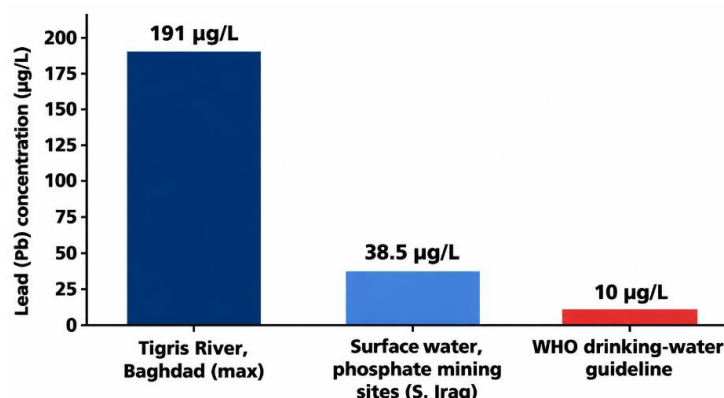


Fig 3: Reported lead concentrations in Iraqi surface water compared with the WHO drinking-water guideline (10 µg/L) [5] [8].

For urban potable water supplies, an integrated multi-index and health risk evaluation conducted in 2026 on Erbil's water concluded that while most physical and chemical indices conformed to WHO guidelines, some heavy metals had concentrations that were above guideline limits at a significant percentage of the sampling points. Lead, for instance, was detected above guidelines at 63.3% of samples, mercury at 53.3%, iron at 30% and arsenic at 20%. For both the non-carcinogenic hazard index ($HI > 2$) and the carcinogenic risk index ($ILCR > 1 \times 10^{-4}$), values were above the acceptable levels. Arsenic contributed the highest level of

carcinogenic hazard ($ILCR = 1.7 \times 10^{-3}$) [21]. An accompanying 2026 study on atmospheric deposition in Erbil's rainwater added another route of exposure through four city zones [22]. The 2021 seasonal study of drinking water in Kirkuk evaluated cancer risk due to combined exposure to benzo(a)pyrene and heavy metals, an example of industrial organic/inorganic contamination from the hydrological system [23]. Table 1 situates the lead findings above alongside comparable reported values for cadmium and arsenic, the two other metals most consistently implicated in Iraqi human-health-risk assessments.

Table 1: Representative reported heavy metal concentrations in Iraqi surface and drinking water compared with WHO drinking-water guideline values [5, 8, 21].

Location	Metal	Reported value (µg/L)	WHO guideline (µg/L)	Approx. exceedance
Tigris River, Baghdad (dry season, max)	Pb	191	10	≈19×
Surface water, southern phosphate-mining sites	Pb	38.5	10	≈4×
Surface water, southern phosphate-mining sites	Cd	4.85	3	≈1.6×
Surface water, southern phosphate-mining sites	As	22.5	10	≈2.3×
Erbil municipal drinking water	Pb	exceeded WHO limit in 63.3% of samples	10	site-dependent
Erbil municipal drinking water	Hg	exceeded WHO limit in 53.3% of samples	6	site-dependent

3.3. Sediments

Two-year (2022-2023) surveys of contamination factor analysis of 120 sediment samples of the Tigris River, post-conflict Mosul, reveal severe cadmium pollution at all sites, moderate lead pollution, and near-background zinc concentrations. The most polluted site is explained by the effects of local hydrogeological conditions on top of existing infrastructure destruction. Supplementary research on heavy metals and polycyclic aromatic hydrocarbons in sediments of the same river and of the Euphrates River, as well as their associations with wastewater discharge were performed in Mosul and Baghdad cities [24, 25]. Another 2023 study on sediments of the same river in Mosul city reports increases in cobalt, copper, cadmium, lead, zinc, and nickel above internationally accepted averages, with anthropogenic rather than natural sources being the cause of the observed trend [26]. The largest sediment dataset described in the selected literature originates from a 25-station survey of dry- and wet-season periods with the evaluation of eleven heavy metals in the Shatt al-Arab River sediments. In this study, sediments are classified as considerably contaminated with iron and molybdenum, moderately contaminated with chromium, zinc, nickel, copper, lead, and manganese, and not contaminated with cobalt and vanadium. Factor analyses revealed the prevalence of anthropogenic origin (industrial, residential, agricultural) rather than lithogenic origin of metal contamination [9]. Another multi-river comparison study accompanies this study on Shatt al-Arab, Tigris, Euphrates, and northwestern Arabian Gulf [27]. Two earlier studies of geo-accumulation and enrichment factors of the Shatt al-Arab River report the same enrichment factors ranging from 0.74 to 14.05, where values larger than 1.5 are associated with anthropogenic enrichment [10]. A 2020 survey in the province of Basra revealed the metal abundance as follows: Fe > Mn > Ni > Zn > Cu > Pb > Cr > Co > Cd, whereas cadmium is still classified as strongly or extremely polluted in spite of the low concentration of the metal [28].

Sunken and abandoned vessel-related sites are characterized by high cadmium contamination due to shipwreck and military activities in addition to low-to-moderate copper, iron, lead, manganese, nickel, and zinc contamination [29]. Microbiological research using bacterial and fungal bioindicators confirms the nickel, chromium, zinc, lead, copper, and cadmium contamination in addition to petroleum hydrocarbon contamination in Shatt al-Arab sediments [30], which supports the conclusion about the prevalence of industrial and oil sector contamination rather than natural weathering as the source of sediment metal contamination. As it follows from the above-presented information, sediment is an active secondary reservoir of heavy metal contamination rather than a historical record since the metal sorbed on fine particulate matter can be re-suspended in the water under

changed pH, redox, and salinity conditions, which has direct implications for bioaccumulation in benthic organisms and, through the aquatic food chain, human exposure through fish and shellfish consumption [9]. The reservoir effect means that improvement of the water contamination levels as a result of effluent treatment may be lagged behind the ecological recovery as long as sediment cadmium contamination remains high.

3.4. Agricultural and Urban Soils

Review of Iraqi soils suggests that the contamination with measurable heavy metals is a relatively new phenomenon, as historical data indicates uncontaminated soils of the country throughout much of the twentieth century, with growing concentrations proportional to industrial development and industrial, conflict, and urban facilities rather than any natural geochemical anomaly [13]. A 2026 multivariate statistical analysis of trace elements across twenty-four sites of the country used principal component and cluster analyses to distinguish between the natural (rock weathering) and anthropogenic contamination, with the leading component accounting for 58.69% of total variation [31].

The 2022-2023 study of post-conflict Mosul soils reveals high variations in lead, zinc, chromium, and nickel levels, as well as dominance of one major anthropogenic source based on the basis of principal component analysis [32], which is consistent with previous localized studies reporting extremely elevated cadmium and substantial lead contamination in the Danfeli stream valley as a result of war-related activity during 2013-2017. Munitions- and demining-related contamination is evident in Halgurd-Sakran National Park, where soils cleared with explosives had nickel levels of up to 328 ppm and chromium levels of up to 308.77 ppm, with the pollution load index exceeding 1 at each station [12]. Industrial and power plant-adjacent soils have specific facility-related contamination profiles, i.e., elevated chromium, nickel, and cobalt near the Ramadi plant, cadmium near the Nasiriyah, and zinc, lead, and copper near the Haidariya facility. In contrast, fly ash emissions are associated with cadmium, zinc, iron, magnesium, and copper contamination above the international soil standards [13]. The soils of the southern Iraqi phosphate mining area revealed cadmium and lead as the most severely elevated (CF = 9.14 and 3.50, respectively) with a composite pollution load index of 2.85 and a potential ecological risk index of 866.5 ("very high ecological risk") due to the contribution of cadmium being more than 63% of the calculated risk [8].

The Kurdistan region soils have become a subject of many studies in recent years. A 2023 GIS-based monitoring of heavy metals in Erbil Governorate agricultural soils [33], 2025 pollution load and principal component analysis of heavy metals in Erbil Governorate stream sediments and associated

soils [34], 2026 geochemical assessment of semi-arid industrial soils in Erbil which includes integration of pollution indices with petroleum hydrocarbon contamination [35], and 2026 trace metal pollution and ecological risk in Koy Sanjaq soils of the northeastern Iraq [36] as well as a related 2026 study of geo-accumulation and enrichment factors in Rawanduz River sediments [37]. Urban dust becomes an additional contamination exposure medium, as a 2026 seasonal study of Duhok City urban dust reveals a pollution load index of 1.92 ("overall pollution") with a comparatively low potential ecological risk index of 31.40 [38]. In contrast, a related 2026 study of airborne dust in Zakho City shows the following concentration order of $Zn > Cu > Pb > Cr > Cd$ and the limitations of seasonally unreplicated sampling for statistical analysis [39].

Wastewater irrigation studies directly show the agronomic relevance of contaminated soils. The study in Erbil reveals lead concentrations up to 46.58 mg/kg in roots, zinc up to 49.85 mg/kg in roots, manganese up to 71 mg/kg in shoots, and cadmium up to 5.06 mg/kg in shoots, with the conclusion about the unsuitability of the tested produce for human consumption as well as higher exposure for children as compared with adults based on daily intake modelling [14].

3.5. Pollution and Ecological Risk Indices

The reviewed studies use a mostly consistent set of standardized indices. Table 2 summarizes the principal indices, their purpose, and a representative Iraqi finding for each.

Table 2: Principal pollution and ecological risk indices applied across the reviewed Iraqi studies, with a representative finding for each.

Index	What it measures	Representative Iraqi finding
Contamination Factor (CF)	Ratio of measured metal concentration to a regional or crustal background value; classifies pollution from low to very high for a single metal.	Cd (CF = 9.14) and Pb (CF = 3.50) in phosphate-mining-affected soils, southern Iraq — the two highest single-metal factors reported [8].
Geo-accumulation Index (I-geo)	Compares present concentration to pre-industrial background, on a logarithmic scale from unpolluted (class 0) to extremely contaminated (class 6).	Cadmium classified as strongly to extremely polluted in Shatt al-Arab sediments despite comparatively low absolute concentration [28, 10].
Enrichment Factor (EF)	Normalizes a metal against a conservative reference element to distinguish natural from anthropogenic enrichment; EF > 1.5 implies anthropogenic input.	EF values of 0.74–14.05 across metals in Shatt al-Arab sediments [10].
Pollution Load Index (PLI)	Composite (geometric mean) of CF values across all measured metals for a site; PLI > 1 indicates overall site contamination.	PLI > 1 at all sites in the Halgurd-Sakran demining study [12]; composite PLI of 2.85 in phosphate-mining soils [8]; PLI of 1.92 in Duhok urban dust [38].
Nemerow Pollution Index (NPI)	Composite index weighting both average and worst-case single-metal contamination; used to flag the most severe metal at a site.	Applied alongside CF in Shatt al-Arab sediment surveys, corroborating iron and molybdenum as the most severely elevated metals [9].
Potential Ecological Risk Index (PERI)	Weights CF by a toxic-response factor specific to each metal, summed across all metals to express overall ecological hazard.	PERI = 866.5 ("very high ecological risk") near southern Iraq phosphate mining, driven mainly by cadmium [8]; PERI = 31.40 (low risk) in Duhok urban dust [38].
Metal Index (MI) / Heavy Metal Pollution Index (HPI)	Water-quality-oriented composite indices comparing measured metal concentrations to permissible drinking-water limits.	MI of 5.8–12.22 (all exceeding the safety threshold) across Tigris River stations in Baghdad [5]; HPI-based classification of localized contamination in Erbil drinking water [21].

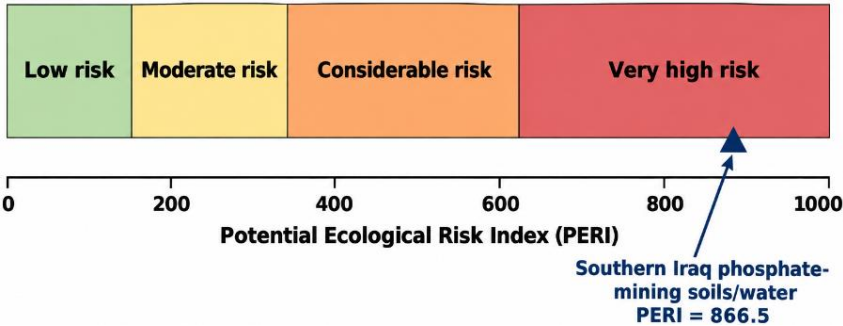


Fig 4: Potential Ecological Risk Index (PERI) classification bands and the value reported for soils and surface water near southern Iraq's phosphate-mining operations, which falls within the 'very high ecological risk' category [8].

It is clear from this cross-indexing exercise that regardless of methodology, location, or team conducting the study, independent research groups working in different cities and in different environmental compartments consistently find cadmium and lead as the metals most elevated and most frequently elevated using diverse indices [9, 8, 31]. The consistent attribution of the elevation, using principal component analysis and factor analysis, to anthropogenic rather than lithogenic sources adds support to the validity of the contamination as an environmental pressure.

3.6. Indicators of Human Health Risk

Human health risk assessment in the reviewed studies is conducted within the usual chronic daily intake framework, where the exposure is calculated using metal concentrations together with ingestion or dermal contact assumptions and compared against a reference dose to calculate a hazard quotient (HQ) for non-carcinogenic effects (combined across metals as a hazard index, HI) or, when coupled with a cancer slope factor, to yield incremental lifetime cancer risk (ILCR); several studies go further and estimate disability-adjusted life years (DALYs) as the measure of health impact [1].

These indicators, applied to Iraqi data, consistently exceed international safety thresholds (HQ or HI > 1; ILCR > 1 × 10⁻⁴ to 1 × 10⁻⁶ depending on the benchmark used) in a number of locations. In post-conflict Mosul, the cumulative hazard index of Tigris River water exceeded 200–300 [6]. In Erbil, hazard index (> 2) and incremental lifetime cancer risk (> 1 × 10⁻⁴) in drinking water exceeded the safety threshold, with arsenic being the key carcinogenic component [21], and in a parallel study on rainwater, the exposure was quantified as atmospheric deposition [22]. In southern Iraq, near the phosphate mining activities, non-carcinogenic hazard indices in children reached up to 16.39 at some sites. At the same time, carcinogenic risk from arsenic and hexavalent chromium exceeded the 10⁻⁶ benchmark [8]. Indoor and household exposure has been estimated in Erbil, including comparative dust exposure in university dormitories [40] and household dust exposure for children and adults [41]; thus expanding the risk quantification into the indoor environment from ambient water and soil. Airborne dust exposure was

assessed in Duhok [38] and in Zakho [39]. A consistent finding, which conforms to general toxicological literature, is that the risk quantified for children is disproportionately high relative to adult exposure at the same ambient concentration in every Iraqi study stratified by age [1]. The second pathway of exposure is dietary exposure via wastewater-irrigated vegetables; it has been independently confirmed in vegetable uptake studies in Erbil, which showed accumulation of cadmium, lead, and other metals in plant edible tissues in concentrations above WHO/FAO safe limits. At the same time, daily intake for children was higher than for adults [14].

3.7. Geographical Synthesis of Hotspots of Contamination

Table 3 summarizes the geographical hotspots reported in the reviewed literature, showing the impacted environmental compartment(s), the metals most frequently involved, the suspected driver and the most convincing index finding.

Table 3: Geographic synthesis of the principal heavy metal contamination hotspots identified across the reviewed Iraqi literature.

Hotspot	Compartment(s)	Dominant metals	Primary suspected driver	Key index finding
Baghdad (Tigris)	Water; garden soils	Pb, Cr, Fe, Cd, Zn, Ni	Untreated sewage and industrial effluent	MI 5.8–12.22 [5]
Mosul (Tigris)	Water; sediment; urban soil	Cd, Pb, Cr, Ni	2016–2017 armed conflict; industrial infrastructure damage	HI 200–300+ [6]; severe CF for Cd [42]
Basra / Shatt al-Arab	Water; sediment; soil (localized)	Cd, Pb, Fe, Mo, Ni	Refinery discharge; shipwreck residues; legacy military materiel	CF: considerable Fe/Mo [9]; very high Cd near shipwrecks [29]
Erbil / Kurdistan region	Drinking water; rainwater; irrigated soil and crops; indoor dust	Pb, As, Hg, Cd, Cu, Cr, Ni	Aging water infrastructure; wastewater irrigation; industrial soils	HI > 2; ILCR > 1×10 ⁻⁴ [21]; Pb up to 46.6 mg/kg in vegetable roots [4]
Southern phosphate belt	Soil; adjacent surface water	Cd, Pb, As	Phosphate mining and land disturbance	PERI = 866.5 [8]
Halgurd-Sakran NP (Kurdistan)	Soil	Ni, Cr, Mn, Co, Cu	Controlled demining detonations	PLI > 1 at all sites [12]
Duhok / Zakho (Kurdistan)	Urban and airborne dust	Ni, Cu, Zn, Mn, Pb, Cr, Cd	Urban and traffic emissions	PLI 1.92, PERI 31.40 [38]; Zn>Cu>Pb>Cr>Cd order [39]
Fallujah / Heet (Euphrates)	Water; sediment	Cd, Cr, Cu, Ni, Pb, Zn	Urban and agricultural discharge	Ecological risk index applied by depth [19]
Kirkuk	Drinking water	Heavy metals + benzo(a)pyrene	Co-located industrial/oil activity	Seasonal cancer risk assessment [23]

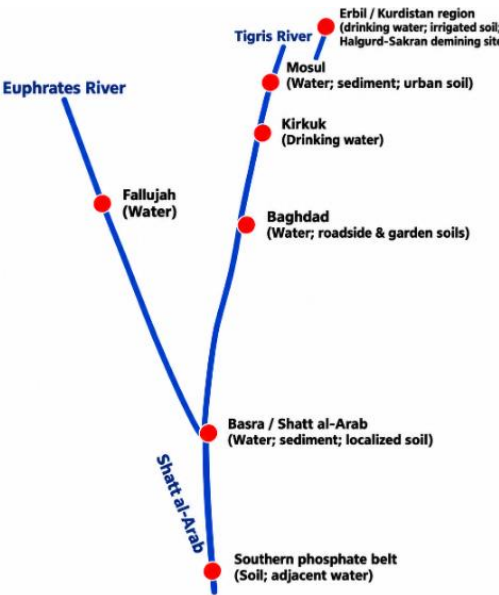


Fig 5: Schematic (not-to-scale) distribution of the contamination hotspots summarized in Table 3, positioned along the Tigris, Euphrates, and Shatt al-Arab river system.

4. Discussion

4.1. Interpretation of Contamination Patterns

Thus, the results obtained form a unified conclusion: cadmium and lead appear to be the most persistent metals in water, sediment, and soil contaminated anthropogenically – industrially, residentially, agriculturally, and by conflict – rather than naturally due to geological background, based on PCA and FA analysis [9, 8, 31]. This coherence holds notwithstanding considerable methodological diversity among studies using Metal Index and Heavy Metal Pollution Index to assess contamination in water [5, 21], contamination factor and geo-accumulation index to assess contamination in sediment [28, 10], and pollution load index and potential ecological risk index to evaluate contamination in soil [8, 12]; all of them attribute the same two metals to the same anthropogenic source.

Another pattern refers to spatial concentration of contamination: it is not uniform across Iraq's rivers or governorates but is associated with particular sources of contamination – dense urban agglomerations (Baghdad), conflict-affected locations (Mosul, Halgurd-Sakran), mining and extraction sites (southern phosphate belt, fossil-fuel power plants), and old urban water infrastructure (Erbil). Reaches and locations without such contamination pressures – like the less industrialized reaches of the Tigris River displays a lower contamination rate, which shows that source proximity, not regional geology, causes this variation.

4.2. Human Health Implications

The human health risk indicators synthesized show that threshold levels of hazard and cancer risk are reached in multiple Iraqi cities. Children disproportionately face the risk associated with these exposures due to drinking water [6, 21], indoor dust [40, 41], and increasingly also wastewater-irrigated produce [14]. Consequently, in risk-based monitoring and remediation efforts, priority should be given to such locations as family housing, schools, and agricultural smallholdings where children live rather than the same contamination rate in adults-only exposure scenarios.

Apart from drinking water, dietary exposure via wastewater-irrigated produce provides another independently proven route of contamination, and indoor dust provides a third one [40, 41, 38, 39]. This evidence, therefore, shows that risk assessments focused on a single pathway will likely underestimate the overall contamination burden faced by populations of most affected areas, and calls for a multi-pathway risk assessment framework, already utilized in several of the most recent studies on Erbil [21, 22, 40, 41].

4.3. Limitations of the Current Evidence Base

The findings that emerge from the synthesized evidence in this review are strong in their core, although there are some aspects of the underlying literature which characterize the boundaries of this review's scope. First of all, the main indices used in primary studies include Metal Index and Heavy Metal Pollution Index for water [5, 21]; the contamination factor and geoaccumulation index for sediments [28, 10]; pollution load and potential ecological risk indices for soils [8, 12]. As these indices are based on different references and background levels, the review makes a qualitative comparison of their results rather than statistical aggregation. Hence, the agreement of these independent methods in singling out cadmium and lead as the dominant anthropogenic metals deserves attention even more.

Secondly, the coverage of space and time in this literature is uneven: the most significant research effort is made in Baghdad, Mosul, Basra and Kurdistan, whereas several governorates located in the center and west of the country are barely represented in the literature with few field campaigns and many studies covering just one season or year [39]. Thirdly, the health risk assessments in the papers under review are based on the standard exposure parameters and reference doses according to international guidelines and are not adjusted for the specific Iraqi body weights, ingestion rates, and diet [1], and, moreover, are mostly calculated on the basis of total metal concentrations. Fourthly, in accordance with the scoping approach taken in this review, the search was performed only in the major databases and institutional reports, but not in accordance with any registered systematic review protocol and without application of quality scoring to individual studies; hence, some literature written in Arabic or published in non-academic sources might have been missed. Nevertheless, the identified priorities do not affect the core of the findings since they are confirmed independently by several research groups in various compartments, locations, and methodologies. On the contrary, they identify the direction for further research: consistent multiseasonal measurements using a fixed metal panel, geographical expansion of the study, bioavailable metal fractions and biomarkers of human exposure, and Iraqi-specific exposure parameters. It will enable future reviews to move from qualitative synthesis to quantitative meta-analysis and trend assessment on a national level.

4.4. Management and Policy Recommendations

The following recommendations target environmental regulators, municipal utilities, and development partners involved in water and soil management in Iraq, sorted in the order of the strongest and most consistent evidence collected in the above review.

- Prioritize investment in municipal and industrial wastewater treatment capacity at the upstream locations of the most heavily polluted reaches of Tigris, Euphrates, and Shatt al-Arab rivers, especially in Baghdad, Mosul, and Basra [9, 2].
- Enforce industrial effluent standards and monitor them routinely and publicly, and create buffer zones and remediation requirements for active and historical mining operations, considering the very high ecological risk in the southern phosphate belt [8].
- Prioritize remediation of documented conflict-pollution hotspots, including post-conflict industrial zones in Mosul [6] [7, 32] and demining sites in Kurdistan [12], taking into account the previous UNEP and UNDP needs assessments [3].
- Restrict or treat the wastewater used for irrigation, and until comprehensive guidelines for safe irrigation are established, redirect the high-risk irrigation water away from those leafy and root vegetables most susceptible to cadmium and lead accumulation [14].
- Expand heavy metal surveillance to the entire food basket beyond vegetables to cereals, dairy products, and freshwater fish, and also expand monitoring of indoor and airborne dust, recently piloted in Erbil, Duhok, and Zakho [40, 41, 38, 39].
- Create a harmonized multi-seasonal national monitoring network for water, sediment, soil, dust, and crop compartments, using a consistent metal panel and index

methodology to allow meaningful long-term trend analysis.

- Incorporate routine human health risk assessment (HQ, HI, ILCR) in the environmental reporting, incorporating human exposure parameters specifically for children who are consistently proven to have higher risk in each Iraqi study [6, 8, 27].

5. Conclusion

There is a set of methodologically independent lines of evidence converging into a coherent picture: Iraq's surface water, sediments, and agricultural soils carry a moderate-to-severe heavy metal burden, which is not evenly spread across the country but concentrated in urban, industrial, adjacent to oil sector and conflict-affected locations. Cadmium and lead appear to be the most persistent and severe metals in water, sediment, and soil contamination, being statistically attributed to anthropogenic rather than natural sources. Based on the data, the human health risk assessments predict exceeding the thresholds of hazard and cancer risk in multiple cities, and children disproportionately face the risk because of the drinking water and increasingly wastewater-irrigated produce. Such contamination can be mitigated through combined actions of wastewater infrastructure investment, enforcement of industrial effluent standards, remediation of conflict- and mining-affected sites, and possible establishment of a sustainable monitoring program.

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