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Assessment of Soil Degradation, Soil and River-Water Contamination, Modeled Human Health Risks, and Vegetation Indicators at Impacted and Reference Sites in Wasit and Baghdad Governorates, Central Iraq

Suhair Sahib Abboud

College of Science, University of Wasit, Al-Kut, Iraq

Abstract

Soil and water quality were assessed at four anthropogenically disturbed land-use sites (petroleum refinery, industrial zone, abandoned agricultural land and municipal waste dump) and one undisturbed reference site in Wasit and Baghdad Governorates, central Iraq, during 2025. Surface soils were analysed for Pb, Cd, Zn, Cu, Ni, pH, electrical conductivity (EC) and organic matter; Tigris River water was monitored upstream and downstream of contamination sources; non-carcinogenic and carcinogenic health risks were modeled following USEPA procedures; and vegetation structure was surveyed. The refinery site (S1) had the highest mean soil concentrations of Pb (312.4 mg/kg), Cd (12.8 mg/kg) and Ni (248.4 mg/kg), corresponding to 4.5, 16.0 and 7.1 times the comparison values used. Mean downstream total dissolved solids (TDS) reached 4,218 ± 386 mg/L in the wet season, 322% above the 1,000 mg/L drinking-water standard, and petroleum hydrocarbons exceeded the 0.05 mg/L guideline by 37- to 85-fold. The modeled hazard index for children at S1 was 1.58, driven mainly by Pb ingestion (HQ = 1.14), whereas the adult hazard index (0.18) and the inhalation cancer risks for Cd and Ni ($< 10^{-7}$) were within acceptable limits. Plant species richness at the impacted sites ranged from 3 to 18 species per plot, compared with 34 at the reference site, representing reductions of 47–91%. These results provide site-specific baseline information for the selected land uses and support prioritizing confirmatory monitoring and remediation planning at the refinery and waste-dump sites.

Keywords

Degraded Land Management,
Heavy Metal Contamination,
Land Rehabilitation,
Soil-Water Quality,
Tigris River Pollution.

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Faculty of Science, ATBU Bauchi

Corresponding Author: Suhair Sahib Abboud, College of Science, University of Wasit, Al-Kut, Iraq. Email: ssaheb@uowasit.edu.iq

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Introduction

Land degradation in Iraq has intensified over recent decades as a result of industrialization, petroleum production, illegal waste dumping and poorly coordinated agricultural practices. Only about 5.6 million hectares of potentially arable land are productively cultivated, while much of the remaining area has become partly or wholly unusable because of salinization, heavy metal pollution, waterlogging or physical disturbance (Ministry of Agriculture of Iraq, 2022). The Tigris–Euphrates river system, the ecological lifeline of the country, receives petroleum refinery effluents, industrial discharges and municipal waste, which degrade water quality for agricultural and domestic use.

Wasit Governorate, on the middle Tigris, illustrates many of these pressures. It hosts major petroleum facilities near the city of Kut and extensive low-lying agricultural land prone to waterlogging and secondary salinization. In Baghdad Governorate, the dominant problems are industrial-zone contamination and the disposal of solid waste generated by a population exceeding 8.5 million. In both governorates, environmental characterization remains limited, and peer-reviewed baseline data on soil and water quality are scarce.

Soil and dust contamination by heavy metals in industrial and urban areas of the Middle East has been widely reported (Al-Swadi et al., 2022), and metals such as Pb, Cd and Ni are of particular concern because of their persistence and toxicity (Tchounwou et al., 2012).

The progressive decline in land and water quality in central Iraq has direct consequences for public health, food security and socio-economic development. Residents living near refineries, industrial facilities and informal dumping sites may be chronically exposed to heavy metals through consumption of crops grown on contaminated soil, inhalation of fugitive dust and drinking water. Children are the most vulnerable group because they ingest more soil per unit body weight, frequently engage in hand-to-mouth behaviour and are more susceptible to metal toxicity (USEPA, 2011). Nevertheless, quantitative health risk assessments based on locally measured contamination data remain scarce in Iraq.

This study evaluated four impacted land-use settings and one undisturbed reference site. The objectives were to: (1) determine the concentrations of Pb, Cd, Zn, Cu and Ni in soils at the five sites; (2) characterize soil pH, EC and organic matter (OM); (3) compare upstream and downstream water-quality parameters of the Tigris River; (4) estimate non-carcinogenic and carcinogenic risks for children and adults under clearly stated exposure assumptions; and (5) compare vegetation composition and diversity between the impacted sites and the reference site. The sites were selected to represent contrasting land uses and are not intended as a representative sample of either governorate.

Materials and Methods

Study area

The study was conducted in Wasit and Baghdad Governorates, central Iraq, which lie approximately 160 km apart along the Tigris River valley (centred at about 32°30′N, 45°50′E and 33°15′N, 44°20′E, respectively). The regional climate is arid to semi-arid (Köppen BWh/BSh), with a mean annual temperature of 22–24 °C and mean annual precipitation of 140–180 mm, falling mainly between November and April, followed by a distinct dry season from May to October. Undisturbed riparian habitats are dominated by *Phragmites australis* reed beds, *Tamarix* spp. shrublands and scattered *Populus euphratica* gallery forest. Four impacted sites (S1–S4) and one undisturbed reference site (S5) were selected to represent contrasting land-use settings (Table 1, Figure 1).

Corresponding Author: Suhair Sahib Abboud, College of Science, University of Wasit, Al-Kut, Iraq. Email: ssaheb@uowasit.edu.iq
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Table 1: Characteristics and approximate locations of four impacted land-use sites (S1–S4) and one undisturbed reference site (S5) in Wasit and Baghdad Governorates, central Iraq.

Site	Land-use / Degradation type	GPS (approx.)	Governorate	Main contamination source	Area (ha)	Distance from Tigris (km)
S1	Petroleum refinery & oil spill area	32°31'N, 45°48'E	Wasit	Petroleum hydrocarbons, heavy metals	6.4	2.1
S2	Active industrial / manufacturing zone	33°18'N, 44°22'E	Baghdad	Industrial effluents, smelting dust	12.8	1.4
S3	Abandoned agricultural land	32°28'N, 45°52'E	Wasit	Pesticides, salinization, waterlogging	38.6	4.8
S4	Urban solid waste dumping site	33°14'N, 44°28'E	Baghdad	Municipal and industrial solid waste	8.2	0.8
S5	Undisturbed reference (riparian shrubland)	32°26'N, 45°44'E	Wasit	None	—	0.3

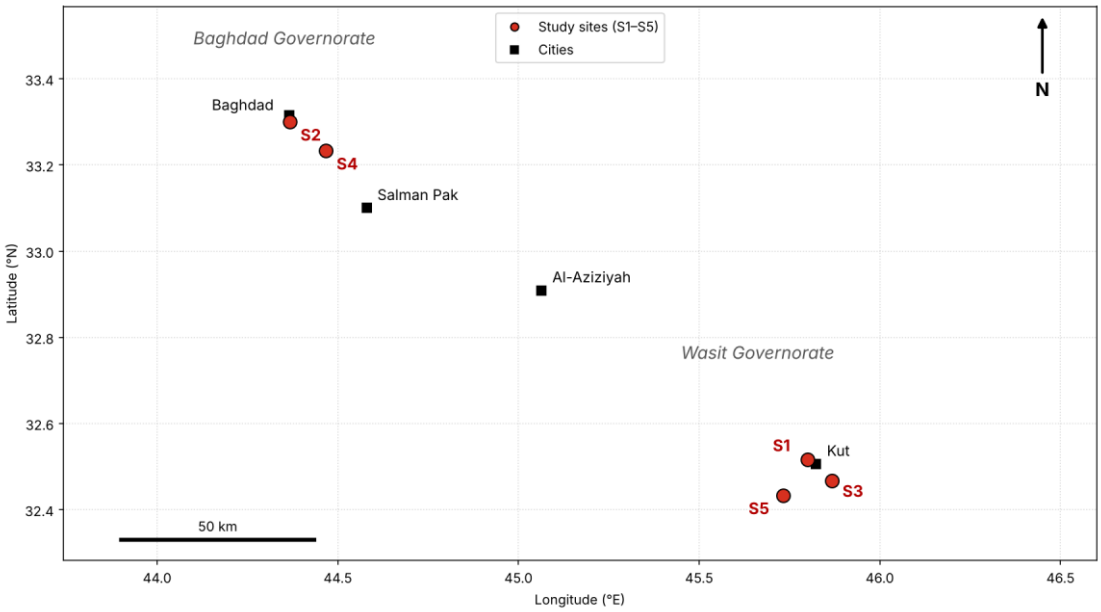


Figure 1: Location of the five study sites (S1–S5) and nearby cities in Wasit and Baghdad Governorates, central Iraq, plotted from the coordinates in Table 1.

Soil sampling and physicochemical analysis

Soil sampling was carried out in January, May, August and November 2025. At each site, five sampling points were established, and samples were collected at depths of 0–10, 10–30 and 30–50 cm. Samples were air-dried for 72 h and sieved through a 2 mm mesh. Soil pH and EC were measured in a 1:2.5 soil:water suspension, OM was determined by Walkley–Black oxidation (Walkley and Black, 1934), and texture was determined by the hydrometer method (Bouyoucos, 1962).

For metal analysis, soil samples were digested with aqua regia (HCl:HNO_3, 3:1) at 120 °C for 3 h, and lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu) and nickel (Ni) were determined by flame atomic absorption spectrophotometry (GBC Avanta, Australia). Quality control included instrument calibration, reagent blanks and analysis of the certified reference material NIST SRM 2710a, with recoveries of 92.8–104.6% and relative standard deviations below 4.8%.

Water quality monitoring

Tigris River water was sampled at three stations for each monitored source (200 m upstream, at the discharge point and 200 m downstream) at approximately two-week intervals. pH, dissolved oxygen (DO), EC and temperature were measured in situ with a calibrated multiparameter probe (YSI Pro 2030), and turbidity with a Hach 2100Qis turbidimeter. Samples were kept cool and delivered to the laboratory within 4 h. TDS were determined gravimetrically at 105 °C, petroleum hydrocarbons by

solvent extraction and infrared spectrophotometry, and dissolved metals in filtered (0.45 μm) samples by ICP-MS (Agilent 8900). Upstream and downstream data from all monitored sources were pooled by season (Table 3), with the dry season defined as June–September and the wet season as November–March.

Human health risk assessment

Potential health risks from chronic exposure to metals in surface soil at S1 were estimated following USEPA guidance (USEPA, 1989, 2004, 2011). Three pathways were considered: incidental soil ingestion, dermal contact and inhalation of resuspended particles. The chronic daily intake (CDI, mg/kg/day) was calculated as $CDI_{ing} = C \times IngR \times EF \times ED \times CF/(BW \times AT)$, $CDI_{derm} = C \times SA \times AF \times ABS \times EF \times ED \times CF/(BW \times AT)$ and $CDI_{inh} = C \times InhR \times EF \times ED/(PEF \times BW \times AT)$, where C is the mean soil concentration (mg/kg), $CF = 10^{-6}$ kg/mg, EF = 350 days/year, ED = 6 years for children and 30 years for adults, BW = 15 and 65 kg, IngR = 200 and 100 mg/day, SA = 2,800 and 5,700 cm^2, AF = 0.2 and 0.07 mg/cm^2, ABS = 0.001, InhR = 7.6 and 20 m^3/day for children and adults, respectively, PEF = 1.36×10^9 m^3/kg, and AT = ED × 365 days (USEPA, 2002, 2004, 2011). The hazard quotient was calculated as HQ = CDI/RfD using oral reference doses commonly applied in soil risk assessment: 3.5×10^{-3} (Pb), 1×10^{-3} (Cd), 0.3 (Zn), 4×10^{-2} (Cu) and 2×10^{-2} (Ni) mg/kg/day. For the dermal pathway, RfDs were multiplied by gastrointestinal absorption factors (0.025 for Cd, 0.04 for Ni and 1 for the other metals) (USEPA, 2004). The hazard index (HI) was obtained by summing HQs across metals and pathways, and HQ or HI > 1 indicates potential adverse effects. Because USEPA IRIS provides no oral cancer slope factors for Pb, Cd or Ni, carcinogenic risk was estimated only for inhalation of Cd and Ni as $CR = EC \times IUR$, where $EC = C \times EF \times ED/(PEF \times AT)$, with AT = 70 years, and the inhalation unit risks (IUR) are 1.8×10^{-3} and 2.4×10^{-4} $(\mu g/m^3)^{-1}$, respectively (USEPA, 2024). CR values between 1×10^{-6} and 1×10^{-4} were considered the acceptable range.

Vegetation assessment

Plant community structure was surveyed in August 2025 in five quadrats per site using stratified nested plots: 20 m × 20 m for woody vegetation, 5 m × 5 m for herbaceous vegetation and 1 m × 1 m for ground cover. All vascular plant species were identified using regional floras (Townsend and Guest, 1966–1985; Al-Rawi and Chakravarty, 1988). Percentage cover was estimated with the Braun-Blanquet cover-abundance method (Braun-Blanquet, 1932), and species were classified as native, naturalized or invasive according to the Iraqi Biodiversity Database. Species richness, the Shannon–Wiener diversity index (H′) (Shannon, 1948) and Pielou's evenness (J′) (Pielou, 1966) were calculated for each site. Soil erosion rates were estimated from erosion-pin measurements at 10 permanent stations per site over the 12-month monitoring period.

Statistical analysis

Data are presented as mean ± standard deviation. Normality was checked with the Shapiro–Wilk test. Relationships among soil, water and vegetation variables were examined by Pearson correlation analysis, with statistical significance set at $p < 0.05$. Because the correlations were computed on pooled observations that are not fully independent within sites, their significance levels should be interpreted with caution.

Results

Heavy metal concentrations in soil

The highest mean concentrations of all five metals were recorded at the petroleum refinery site (S1), followed by the industrial site (S2) and the waste-dump site (S4), while the lowest were found at the reference site (S5) (Table 2, Figure 2). At S1, Pb, Cd and Ni concentrations were 312.4 ± 18.6, 12.8 ± 1.4 and 248.4 ± 18.4 mg/kg, respectively, approximately 4.5, 16.0 and 7.1 times the corresponding comparison values (70, 0.8 and 35 mg/kg).

Metal concentrations at the abandoned agricultural site (S3) were lower than at S1, S2 and S4 but higher than at S5, and Zn at S3 (212.6 ± 18.6 mg/kg) exceeded its comparison value (150 mg/kg). Soil pH was neutral to slightly alkaline at all sites (7.2–7.9), whereas EC exceeded the salinity threshold of 4.0 dS/m at S1, S2 and S4 (8.4, 6.2 and 5.4 dS/m, respectively). Organic matter was lowest at S1 (0.42%) and highest at S5 (3.84%) (Table 2, Figure 3).

Table 2: Surface-soil (0–10 cm) metal concentrations and physicochemical characteristics at the five sites, August 2025 (mean ± SD, n = 5 per site).

Site	Pb (mg/kg)	Cd (mg/kg)	Zn (mg/kg)	Cu (mg/kg)	Ni (mg/kg)	pH (1:2.5)	EC (dS/m)	OM (%)
S1	312.4±18.6	12.8±1.4	642.3±36.8	184.6±14.2	248.4±18.4	7.2±0.3	8.4±0.6	0.42±0.08
S2	248.6±16.2	9.4±1.1	498.4±28.4	142.3±11.8	196.8±14.6	7.6±0.4	6.2±0.5	0.84±0.12
S3	142.3±12.4	4.2±0.8	212.6±18.6	68.4±8.4	124.6±12.2	7.8±0.3	3.8±0.4	1.28±0.18
S4	198.5±14.8	7.6±0.9	384.2±24.2	112.8±10.4	168.4±14.8	7.4±0.3	5.4±0.5	0.62±0.10
S5	18.2±2.4	0.6±0.1	38.4±4.2	14.2±2.1	28.6±3.8	7.9±0.2	1.2±0.2	3.84±0.42
Comparison value*	**70**	**0.8**	**150**	**50**	**35**	**6.5–8.5**	**<4.0**	—

*Indicative screening values for metals, not legally binding soil limits in Iraq; pH (6.5–8.5) and EC (< 4.0 dS/m) thresholds refer to agricultural soil quality (Richards, 1954).

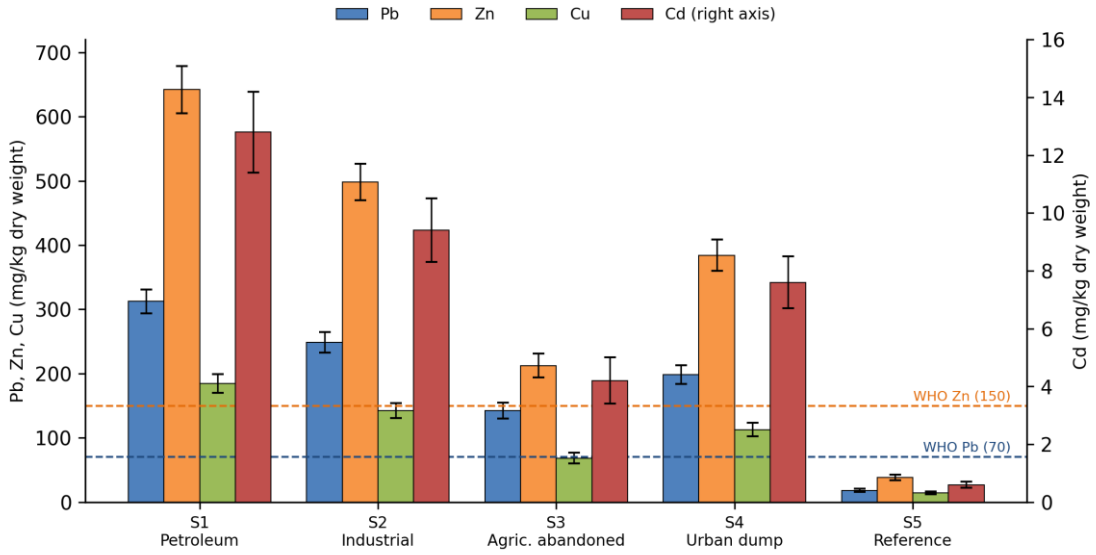


Figure 2: Heavy metal concentrations of Pb, Zn, and Cu (left axis) and Cd (right axis; secondary scale) across the five study sites. Error bars represent standard deviation (n = 5). Dashed horizontal lines indicate comparison values for Pb (70 mg/kg) and Zn (150 mg/kg)

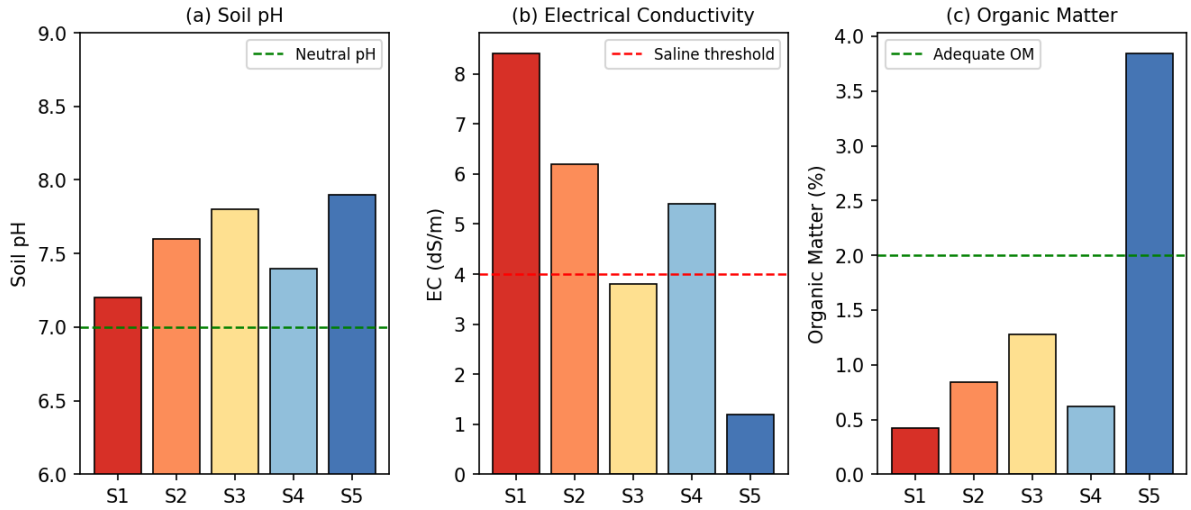


Figure 3: Soil physicochemical properties across the five study sites: (a) pH, (b) electrical conductivity (EC), and (c) organic matter content. Dashed lines indicate recommended thresholds for agricultural land quality. Error bars = standard deviation (n = 5)

Tigris River water quality

Downstream water quality was markedly poorer than upstream in both seasons (Table 3). Mean downstream pH decreased to 6.5 ± 0.6 in the dry season and 5.7 ± 0.9 in the wet season, compared with 7.6–7.9 upstream. Mean downstream TDS was 2,842 ± 248 mg/L in the dry season and 4,218 ± 386 mg/L in the wet season, exceeding the 1,000 mg/L standard by 184.2% and 321.8%, respectively, whereas upstream TDS remained close to the standard (842–1,082 mg/L).

Mean downstream petroleum hydrocarbon concentrations were 1.84 ± 0.28 mg/L (dry) and 4.24 ± 0.64 mg/L (wet), i.e., 36.8 and 84.8 times the 0.05 mg/L guideline. Downstream DO averaged 4.8 ± 0.8 mg/L in the dry season and 2.4 ± 1.1 mg/L in the wet season, 4% and 52% below the 5 mg/L criterion. Turbidity and dissolved Pb and Ni also exceeded their respective standards downstream in both seasons, with the highest values in the wet season.

Table 3: Upstream and downstream Tigris River water characteristics in the dry (June–September) and wet (November–March) seasons (mean ± SD, n = 24 per station group per season, pooled across monitored sources). Percentage exceedance = (mean – standard)/standard × 100; for DO, the percentage below the minimum is shown.

Parameter	Upstream dry season	Upstream wet season	Downstream dry season	Downstream wet season	% exceed dry	% exceed wet	Iraqi/WHO standard
pH	7.9±0.3	7.6±0.4	6.5±0.6	5.7±0.9	—	Below range	6.5–8.5
TDS (mg/L)	842±62	1082±84	2842±248	4218±386	184.2%	321.8%	<1000 mg/L
Turbidity (NTU)	42±8	84±14	186±28	412±56	3,620%	8,140%	<5 NTU
DO (mg/L)	8.4±0.4	7.8±0.6	4.8±0.8	2.4±1.1	4%	52%	>5 mg/L
Pb (µg/L)	4.2±0.8	6.4±1.2	42.8±6.4	88.4±14.2	328.0%	784.0%	<10 µg/L
Ni (µg/L)	8.4±1.2	12.4±2.4	68.4±8.4	142.8±18.4	242.0%	614.0%	<20 µg/L
Petroleum HC (mg/L)	0.04±0.01	0.06±0.02	1.84±0.28	4.24±0.64	3,580%	8,380%	<0.05 mg/L

Human health risk assessment

Modeled non-carcinogenic risks at S1 are summarized in Table 4 and Figure 4. For children, only Pb had an HQ above 1 (1.14), followed by Cd (0.18), Ni (0.17), Cu (0.06) and Zn (0.03), giving a hazard index of 1.58. Incidental soil ingestion accounted for about 98% of this value, whereas dermal contact and dust inhalation contributed little. For adults, all HQ values were below 1, and the HI was 0.18.

Inhalation cancer risks for Cd and Ni were 1.4×10^{-9} and 3.6×10^{-9} for children and 7.0×10^{-9} and 1.8×10^{-8} for adults, all far below the 1×10^{-6} threshold. These values are modeled estimates and do not represent observed health outcomes.

Table 4: Modeled hazard quotients (HQ) and inhalation cancer risks (CR) for children and adults at the petroleum refinery site (S1). Hazard index (HI): children 1.58, adults 0.18. CR was not calculated for Pb (no USEPA IRIS slope factor) or for Zn and Cu (non-carcinogenic).

Metal	HQ children	HQ adults	Non-cancer risk (children)	CR children	CR adults	Cancer risk level	Primary exposure pathway
Pb	1.14	0.13	HQ > 1	—	—	Not assessed	Soil ingestion
Cd	0.18	0.02	HQ < 1	1.4×10^{-9}	7.0×10^{-9}	Negligible (< 10^{-6})	Soil ingestion
Zn	0.03	0.003	HQ < 1	—	—	Non-carcinogenic	Soil ingestion
Cu	0.06	0.007	HQ < 1	—	—	Non-carcinogenic	Soil ingestion
Ni	0.17	0.02	HQ < 1	3.6×10^{-9}	1.8×10^{-8}	Negligible (< 10^{-6})	Soil ingestion

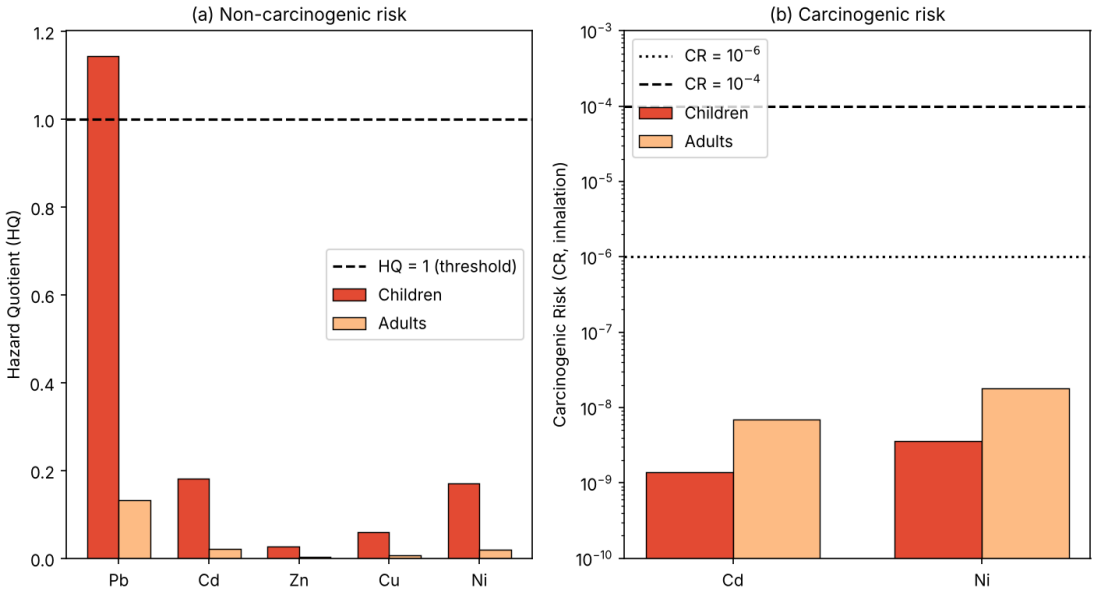


Figure 4: Non-carcinogenic hazard quotients (a) and inhalation carcinogenic risks of Cd and Ni (b, logarithmic scale) for children and adults at the petroleum refinery site (S1). Dashed lines indicate HQ = 1 and CR = 1×10^{-4}; the dotted line indicates CR = 1×10^{-6}.

Vegetation structure and land cover

Vegetation at the four impacted sites differed markedly from that at the reference site (Table 5, Figure 5). Mean species richness was 3 ± 1 at S1, 8 ± 2 at S2, 18 ± 3 at S3 and 5 ± 1 at S4, compared with 34 ± 4 species per plot at S5, corresponding to reductions of 91.2%, 76.5%, 47.1% and 85.3%, respectively. Bare soil cover at the impacted sites ranged from 33.4% (S3) to 73.4% (S1), compared with 20.8% at S5.

Among the impacted sites, native cover was highest at S3 (38.4 ± 5.2%), whereas invasive cover was highest at S4 (42.6 ± 6.2%). The Shannon index followed the same pattern as species richness, ranging from 0.28 at S1 to 1.84 at S3, compared with 2.84 at S5. Estimated erosion rates ranged from 8.4 ± 1.6 t/ha/year at S3 to 22.4 ± 3.2 t/ha/year at S1, compared with 1.2 ± 0.3 t/ha/year at S5, and litter depth was lowest at S1 (0.1 cm) and highest at S5 (6.8 cm).

Table 5: Vegetation community structure and land cover indicators across the five study sites in Wasit and Baghdad, Iraq (August 2025 survey, n = 5 quadrats per site)

Site	Native cover (%)	Invasive cover (%)	Species richness (no./plot)	Shannon index (H')	Bare soil (%)	Litter depth (cm)	Erosion rate (t/ha/yr)
S1 (Petroleum)	4.2±1.2	22.4±4.2	3±1	0.28±0.08	73.4±6.8	0.1±0.1	22.4±3.2
S2 (Industrial)	12.6±2.8	18.6±3.4	8±2	0.94±0.14	68.8±5.4	0.4±0.2	16.8±2.4
S3 (Agric. Abandoned)	38.4±5.2	28.2±4.8	18±3	1.84±0.22	33.4±4.8	2.4±0.6	8.4±1.6
S4 (Urban Dump)	8.4±1.8	42.6±6.2	5±1	0.48±0.10	49.0±5.6	0.2±0.1	18.2±2.8
S5 (Reference)	72.8±4.8	6.4±1.4	34±4	2.84±0.24	20.8±3.2	6.8±0.8	1.2±0.3

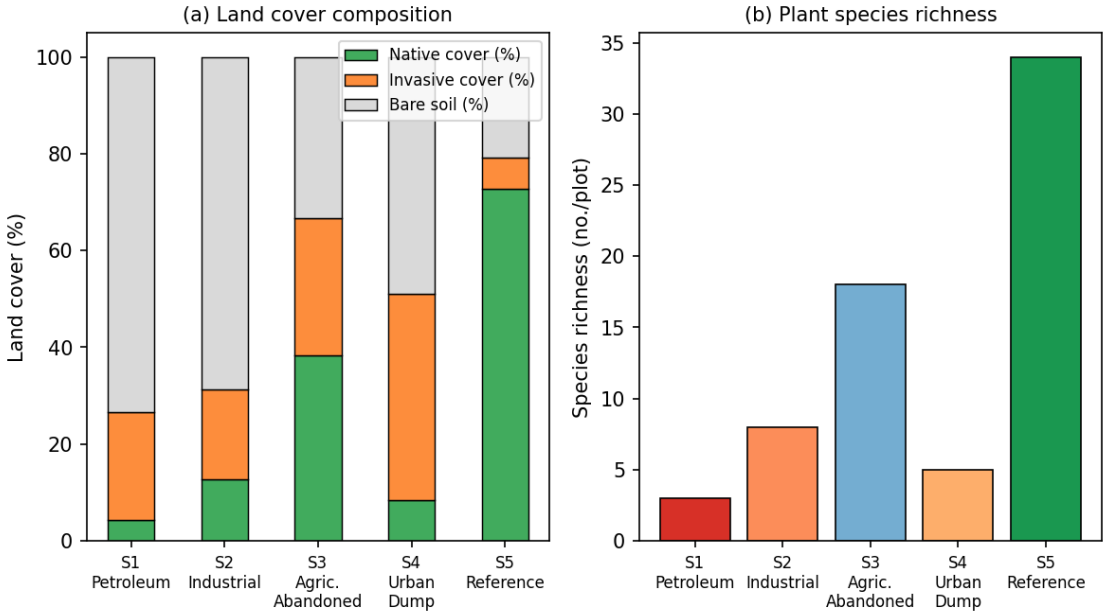


Figure 5: Vegetation land cover composition (a) and plant species richness (b) across the five study sites. Panel (a) shows stacked proportions of native species cover, invasive species cover, and bare soil. Error bars in (b) represent standard deviation (n = 5)

Correlation analysis

Pearson correlations among soil, water and vegetation variables are presented in Table 6. Pb, Cd and Ni were strongly intercorrelated (r = 0.868–0.924) and were negatively correlated with soil pH (r = –0.912, –0.888 and –0.862, respectively) and species richness (r = –0.812, –0.784 and –0.768, respectively; all $p < 0.01$). EC was strongly correlated with TDS (r = 0.912), and DO with species richness (r = 0.924) (both $p < 0.01$). These correlations describe associations across the pooled data set and do not by themselves demonstrate causal relationships.

Table 6: Pearson correlation matrix of soil, water and vegetation variables (n = 100).

Variable	Pb	Cd	Ni	pH	EC	TDS	DO	Species rich.
Pb	1.000	0.924**	0.896**	-0.912**	0.882**	0.856**	-0.784**	-0.812**
Cd	0.924**	1.000	0.868**	-0.888**	0.854**	0.832**	-0.762**	-0.784**
Ni	0.896**	0.868**	1.000	-0.862**	0.828**	0.804**	-0.748**	-0.768**
pH	-0.912**	-0.888**	-0.862**	1.000	-0.814**	-0.788**	0.842**	0.876**
EC	0.882**	0.854**	0.828**	-0.814**	1.000	0.912**	-0.724**	-0.742**
TDS	0.856**	0.832**	0.804**	-0.788**	0.912**	1.000	-0.698**	-0.718**
DO	-0.784**	-0.762**	-0.748**	0.842**	-0.724**	-0.698**	1.000	0.924**
Species rich.	-0.812**	-0.784**	-0.768**	0.876**	-0.742**	-0.718**	0.924**	1.000

** *Correlation is significant at the 0.01 level (2-tailed).*

Discussion

Soil metal concentrations at the impacted sites, particularly the refinery site, were well above those at the reference site and above the comparison values used. Concentrations at the reference site (S5) were comparable to or lower than world average soil concentrations of Pb, Zn, Cu and Ni (27, 70, 38.9 and 29 mg/kg, respectively), and only slightly higher for Cd (0.41 mg/kg) (Kabata-Pendias, 2011), supporting its use as a local background. In contrast, the enrichment at S1, S2 and S4 is consistent with inputs from petroleum refining, industrial activity and waste disposal, as reported for industrial and urban areas elsewhere in the region (Al-Swadi et al., 2022). The greatest relative enrichment was observed for Cd, a metal of particular concern because of its mobility and toxicity (Tchounwou et al., 2012). The elevated EC and low OM at S1, S2 and S4 indicate that salinization and organic matter loss accompany metal

contamination at these sites, both of which reduce soil fertility and hinder vegetation recovery.

The consistent downstream increases in TDS, petroleum hydrocarbons, turbidity and dissolved metals, together with the decline in DO, indicate substantial pollutant loading between the upstream and downstream stations. Wet-season downstream TDS was about 4.2 times the 1,000 mg/L Iraqi drinking-water standard (COSQC, 2009), which also corresponds to the palatability threshold noted by WHO (2022), and petroleum hydrocarbon concentrations were 37–85 times the 0.05 mg/L guideline. DO concentrations below 5 mg/L, particularly the wet-season mean of 2.4 mg/L, are insufficient to support many aquatic organisms. Attributing this pollution to specific discharges would require targeted source-tracking studies.

The health risk assessment indicates a potential non-carcinogenic concern for children at S1 (HI = 1.58), almost entirely due to incidental ingestion of Pb-contaminated soil (HQ = 1.14). Children were at higher risk than adults (HI = 0.18) because of their higher soil ingestion rate relative to body weight (USEPA, 2011). Inhalation cancer risks for Cd and Ni were several orders of magnitude below 1×10^{-6}, indicating negligible carcinogenic risk from dust inhalation; however, carcinogenic risk through ingestion could not be evaluated because USEPA IRIS provides no oral slope factors for these metals. Because no biomonitoring or clinical data were collected, these results indicate potential rather than demonstrated health effects. Given the dominant contribution of Pb, blood lead screening of children living near S1 is recommended as a follow-up.

Plant species richness and diversity were strongly reduced at the impacted sites, with the greatest losses at the refinery (91%) and waste-dump (85%) sites. The negative correlations of species richness with soil Pb, Cd and Ni, and its positive correlation with soil pH, are consistent with metal phytotoxicity and soil chemical stress. However, metal concentrations, salinity, physical disturbance and substrate properties co-varied among sites, so their individual effects cannot be separated with the present cross-sectional design. The high invasive cover at S4 and the high erosion rates at S1 and S4 suggest that these sites are unlikely to recover without active rehabilitation, whereas the relatively high native cover and diversity at S3 indicate a greater potential for natural recovery once salinity and waterlogging are managed.

The strong correlations of EC with soil metals and TDS suggest that EC could serve as a rapid, low-cost screening indicator for prioritizing sites for detailed analysis. Nevertheless, this relationship should be validated with independent data before EC is used as a substitute for laboratory metal determination.

This study has some limitations. The sites were purposively selected and represent individual land uses rather than the governorates as a whole; only one reference site was included; and vegetation was surveyed on a single occasion. In addition, health risks were modeled from soil concentrations and standard exposure factors rather than from measured exposure, and the correlation analysis was based on pooled observations.

Conclusion

Soils at the four impacted land-use sites contained higher concentrations of Pb, Cd, Zn, Cu and Ni than the local reference site, with the highest levels at the petroleum refinery site, where Pb, Cd and Ni were 4.5, 16.0 and 7.1 times the comparison values. Tigris River water downstream of the contamination sources showed elevated TDS (up to 4,218 mg/L), petroleum hydrocarbons, turbidity and dissolved metals, together with depleted DO. The modeled hazard index for children at the refinery site (1.58), mainly due to Pb ingestion, indicated potential non-carcinogenic risk, whereas adult and cancer risks were within acceptable limits, and plant species richness at the impacted sites was 47–91% lower than at the reference site. These findings apply to the sampled locations and provide baseline information for environmental management in Wasit and Baghdad Governorates.

Based on these findings, the following priorities are recommended: (1) confirmatory sampling, metal speciation and source identification at S1 and S4 before remediation decisions are made; (2) regular monitoring of effluent discharges and downstream Tigris water quality; (3) field trials of soil amendments and salinity management at the abandoned agricultural site (S3); (4) leachate control at the S4 dumping site; and (5) a community exposure

and biomonitoring programme in areas near the refinery and dumping sites.

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