

Matched Riverbank–Channel Elemental Profiles along the Tigris River: An Exploratory Compositional Survey

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Scientific Research Commission

Research Article

Keywords: Tigris River, channel sediment, riverbank soil, X-ray fluorescence, compositional data, Aitchison distance, restricted permutation

Posted Date: July 31st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10459205/v1>

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Additional Declarations: No competing interests reported.

Abstract

Riverbank soils and channel sediments are dynamically exchanged during erosion and deposition, yet their geochemical relationships are rarely evaluated as matched observations. This study compared channel sediment and right- and left-bank surface soils at seven Tigris River reaches between Baghdad and Wasit during summer 2024. Forty-one elements were screened by energy-dispersive X-ray fluorescence. The 21 samples were analysed as seven matched reach sets of three samples each using exact restricted element-wise permutation, Monte Carlo restricted multivariate permutation, false-discovery-rate control, centered log-ratio transformation, principal component analysis, Ward clustering, and Aitchison distance. The first two CLR principal components explained 57.1% of compositional variance. The exploratory matched-set compositional test indicated no statistically detectable consistent sample-type effect (Monte Carlo restricted-permutation $p = 0.1439$, $R^2=0.200$). After element-wise FDR correction, the survey provided insufficient evidence of a consistent difference among the three media for any of the 41 elements. The magnitude and direction of channel–bank contrasts varied among reaches, and the descriptive sequence of site-specific Aitchison distances was not monotonic. The observed profiles are consistent with, but do not demonstrate, local hydraulic sorting and bank–channel exchange; they do not establish metal bioavailability, ecological risk, or river-water suitability. The matched survey design and compositional framework provide a transparent baseline for targeted monitoring of Tigris sediment redistribution.

Introduction

The Tigris corridor across the Mesopotamian Plain is an active sediment-routing system in which channel deposits, bank erosion, floodplain storage and human modification interact. Suspended sediments contain mixed carbonate and silicate mineral assemblages, and their texture and mineralogy vary downstream [1, 2]. Tributary and floodplain studies likewise show that provenance and hydraulic sorting strongly influence elemental composition [3, 4]. Consequently, a high total concentration in an XRF scan is not by itself evidence of anthropogenic contamination.

Environmental pressure nevertheless makes the Baghdad–Wasit corridor important. Wastewater inputs, agricultural return flow, oil-related activities and bank instability can alter local sediment delivery and element partitioning [5–8]. Previous studies have generally evaluated water, sediment or soil separately, and several have relied on unpaired site comparisons or conventional multivariate analysis [9–11]. Such designs cannot directly quantify how channel material differs from the two adjacent banks at the same reach.

A second issue is statistical. Multi-element XRF outputs form a positive composition constrained by the reported total. Correlations and PCA applied to raw percentages may therefore contain closure-induced relationships. Log-ratio geometry provides a coherent alternative: relative information is represented by centered log-ratios, and Euclidean distance in that space is the Aitchison distance [12, 13]. Matching the three sample media within each reach further requires restricted—not unrestricted—permutation.

This exploratory cross-sectional survey examined whether channel sediment, right-bank soil and left-bank soil showed consistent differences in their 41-element profiles across seven Tigris reaches. The objectives were to (i) quantify matched differences among the three media; (ii) control multiplicity across the element panel; (iii) identify the principal compositional gradients and sample groupings; and (iv) describe reach-specific channel–bank dissimilarity. The scope was descriptive and comparative: it was not a randomized experiment, a pollution-risk assessment or a basis for causal source attribution.

Materials and methods

Study design and sampling

Sampling was conducted during summer 2024 at seven named reaches ordered from Baghdad toward Wasit: Bridge, Tuwaitha, Al-Mada'in, Al-Aziziyah, Al-Nu'maniyah, Kut Barrage and Sheikh Saad (Fig. 1). This was a purposive river-corridor survey rather than a randomized or cyclic experiment. The number and placement of reaches were constrained by the longitudinal structure, accessibility and hydromorphological organization of the river corridor. At each reach, one channel-sediment sample and one surface-soil sample from each bank were analysed, producing 21 observational units arranged in seven matched reach sets. The reach—not the individual sample—was the independent inferential unit; the three samples within a reach were paired observations and were not treated as independent replicates. Right and left banks were defined from the perspective of an observer looking downstream. Figure 1 locates the named reaches using geographic centroids and does not claim sub-metre field positions.

Sample preparation and XRF screening

Samples were collected and prepared using the laboratory workflow previously applied to Iraqi soils by Al-Gburi et al. [11]. Material was air-dried, disaggregated, homogenized, passed through a 2-mm sieve and analysed at the Ministry of Science and Technology laboratory in Baghdad using a SPECTRO XEPOS benchtop energy-dispersive X-ray fluorescence instrument. Calibration curves were established using the laboratory reference-material procedure reported by Al-Gburi et al. [11]. Analytical blanks, duplicate samples and triplicate measurements were included; recoveries were 90–105% and triplicate relative standard deviations were below 10%. Detection and quantification limits were evaluated according to IUPAC criteria within an ISO/IEC 17025:2017 laboratory quality framework. Results were supplied as mass percentages and converted to mg kg^{-1} using the relation $1\% = 10,000 \text{ mg kg}^{-1}$. XRF results were interpreted as total-element screening results rather than as measurements of bioavailable fractions.

Data integrity and scale reconciliation

The source workbook was parsed from the dedicated channel-sediment, right-bank and left-bank blocks. Values were not replaced merely because they were statistically extreme. Four major-element entries were restored by a factor of 100 only where the worksheet’s independently reported sample total showed the same deficit (Table 1). The unmodified transcription was retained, and all conclusions were rechecked against it. No low-level trace-element value was altered.

All 861 element-by-sample entries used in the compositional analysis were finite and strictly positive as supplied. The dataset therefore contained no zeros or non-detect codes requiring multiplicative replacement before CLR transformation. Low-level positive readings were retained without substitution and were interpreted as screening measurements; Cd, Hg, Ag, Te and Tl were not used for regulatory classification.

Table 1
Auditable scale restorations. The entered values remain documented in the data-integrity record

Medium	Reach	Element	Entered (%)	Analysed (%)	Basis
Channel sediment	Al-Nu'maniyah	Si	0.0352	3.52	Reconciliation with reported total
Right bank	Sheikh Saad	Si	0.04018	4.018	Reconciliation with reported total
Left bank	Tuwaitha	Si	0.04002	4.002	Reconciliation with reported total
Right bank	Al-Mada'in	K	0.007761	0.7761	Reconciliation with reported total

Exact blocked element-wise inference

For each element, the three sample media were ranked within each reach. The global null hypothesis of exchangeability of medium labels was tested by enumerating all $6^7 = 279,936$ within-reach permutations. Pairwise contrasts were then evaluated on ln-ratios using all $2^7 = 128$ sign configurations. Benjamini–Hochberg adjustment controlled the false discovery rate across the 41 global tests and, separately, across the complete family of 123 pairwise tests [14]. Medians and matched log-ratios were used as effect summaries. Exploratory uncertainty intervals were obtained by resampling the seven matched reaches with replacement 10,000 times and taking the 2.5th and 97.5th percentiles of the bootstrap distribution (seed 2407). These intervals were not multiplicity-adjusted and were not used as substitutes for the FDR-controlled tests.

Exploratory compositional multivariate model

For sample i with $D = 41$ positive parts, the centered log-ratio coordinate was:

$$clr(x_{ij}) = \ln[x_{ij} / g(x_{.j})], \quad g(x_{.j}) = (\prod_{i=1}^n x_{ij})^{1/n}$$

1

PCA and Ward clustering were applied to the CLR matrix. The compositional distance between media a and b was:

$$d_A(x_a, x_b) = \left\{ \sum_j [clr(x_{aj}) - clr(x_{bj})]^2 \right\}^{1/2}$$

2

Before reach centering, the matched-set structure was represented conceptually as:

$$clr(x_{ijk}) = \mu + \tau_i + u_j + \epsilon_{ijk}$$

3

where τ_i denotes the channel/right/left sample-type component and u_j denotes the matched reach set. The CLR vector for each observation was then centered on its reach mean, eliminating u_j before calculation of the sample-type sum of squares. With 21 observations and seven removed reach means, the centered total had 14 degrees of freedom; sample type used 2 df and the residual used 12 df. The pseudo-F statistic was $(SS_{type}/2)/(SS_{residual}/12)$, and R^2 was SS_{type}/SS_{total} . Significance was assessed by a Monte Carlo restricted-permutation test [15] using 19,999 within-reach permutations of the three medium labels (seed 2024); this multivariate test was therefore not described as exact. PCA used singular-value decomposition, and clustering used Ward linkage with Euclidean distance in CLR space. Analyses were run in Python 3.12.13 using NumPy 2.3.5, pandas 2.2.3, SciPy 1.17.0 and scikit-learn 1.8.0.

Evidential boundaries

No enrichment factor, contamination factor, geoaccumulation index or ecological-risk index was calculated because neither a validated local background value nor a bioavailable fraction was available. The soil/sediment XRF data cannot be used to calculate water-quality or irrigation-suitability indices. Spatial interpolation and machine-learning prediction were also excluded because 21 co-located, blocked observations are insufficient for independent validation.

Results

Concentration structure

Table 2
Median concentrations (mg kg⁻¹), Kendall's coefficient of concordance and exact blocked tests. FDR q values control the 41-element family

Element	Sediment	Right bank	Left bank	Kendall W	Exact p	FDR q
Ca	59260.00	80470.00	79670.00	0.796	0.0012	0.0501
Si	38950.00	39910.00	39790.00	0.020	0.9640	0.9881
Fe	21250.00	36560.00	37600.00	0.388	0.0854	0.1751
Al	1449.00	4885.00	4997.00	0.429	0.0515	0.1173
K	4852.00	7870.00	8291.00	0.510	0.0272	0.1173
Ti	1718.00	2386.00	2487.00	0.327	0.1118	0.2183
Cr	220.00	278.00	275.00	0.158	0.3581	0.4894
Ni	36.20	115.10	126.70	0.429	0.0515	0.1173
Zn	27.90	54.60	67.90	0.429	0.0515	0.1173
Cu	10.70	34.40	38.00	0.510	0.0272	0.1173
Pb	9.10	18.30	15.00	0.429	0.0515	0.1173
As	3.20	3.80	5.40	0.429	0.0515	0.1173
Cd	4.00	4.30	4.40	0.046	0.7370	0.8394
Hg	2.50	2.90	2.90	0.015	0.9280	0.9881

Calcium, silicon and iron dominated all three media, followed by potassium and aluminium (Table 2; Fig. 2). For 21 elements, the left bank had the largest median; the right bank did so for 18 elements, and the channel sediment did so for 2. These counts are descriptive rather than evidence of a uniform medium effect. After FDR correction, the data provided insufficient evidence of a consistent element-wise difference among the media. This result does not demonstrate equivalence or absence of differences; the survey describes matched shifts across seven reaches and does not estimate within-reach population variance.

Restricted multivariate test and ordination

The exploratory matched-set compositional test gave pseudo-F = 1.504, R²=0.200 and Monte Carlo restricted-permutation p = 0.1439. CLR-PC1 explained 44.0% and CLR-PC2 13.0% (57.1% cumulatively). The elements with the strongest combined PC1–PC2 loadings were Cl, S, Al, Mo, Hg, Ba, U, and W. Ordination and Ward clustering showed that media were not separated by a simple single-axis gradient; several samples remained closer to another medium at the same or a neighbouring reach than to all samples of their nominal class (Fig. 3).

Table 3
Decomposition of CLR sum of squares for the exploratory matched-set multivariate test. The p value is based on 19,999 Monte Carlo permutations restricted within reaches

Source	df	SS	MS	Pseudo-F	R ²	p
Sample type	2	70.585	35.293	1.504	0.200	0.1439
Residual	12	281.682	23.473	—	0.800	—
Centered total	14	352.267	—	—	1.000	—

Matched channel–bank dissimilarity

Table 4
Site-wise Aitchison distances calculated from the complete 41-element composition

Matched contrast	Median	Minimum	Maximum
Channel sediment–Left bank	6.627	4.331	10.078
Channel sediment–Right bank	7.195	5.855	9.558
Right bank–Left bank	5.637	3.517	8.098

Aitchison distances varied markedly among reaches (Fig. 4). In this seven-reach survey, neither bank was descriptively the closer analogue of channel sediment throughout the corridor. The plotted sequence did not show a clear monotonic pattern, but a downstream trend was not tested because survey-grade river-kilometre distances were unavailable. Large distances identify abrupt changes in the full relative profile, but they do not identify a pollution source.

Priority-element contrasts and sensitivity

Table 5 Twelve smallest global probabilities with Kendall's *W* effect sizes. Statistical retention is based on *FDR* $q < 0.05$

Element	Kendall W	Exact p	FDR q	Interpretation
Ca	0.796	0.0012	0.0501	Not retained
Tl	0.526	0.0075	0.0691	Not retained
Mn	0.633	0.0084	0.0691	Not retained
Co	0.633	0.0084	0.0691	Not retained
W	0.633	0.0084	0.0691	Not retained
P	0.571	0.0162	0.1109	Not retained
K	0.510	0.0272	0.1173	Not retained
Cu	0.510	0.0272	0.1173	Not retained
Rb	0.510	0.0272	0.1173	Not retained
V	0.464	0.0364	0.1173	Not retained
Al	0.429	0.0515	0.1173	Not retained
Ni	0.429	0.0515	0.1173	Not retained

None of the 123 pairwise element contrasts remained significant after family-wide FDR control. Figure 5 reports bank-to-channel median log-ratios and exploratory paired-bootstrap uncertainty intervals for Cr, Ni, Cu, Zn, As, Cd, Hg and Pb without converting total-XRF abundance into a risk classification. Repeating the multivariate calculation on the unmodified transcription yielded $R^2=0.180$, compared with 0.200 after scale reconciliation. This sensitivity analysis assessed whether the overall interpretation depended on the four documented entries, without deleting observations.

Table 6 Sensitivity of the principal inferential and multivariate results to reconciliation of the four documented major-element entries

Sensitivity metric	Unmodified vs reconciled result
Matched multivariate test	R^2 0.180 vs 0.200; p 0.1981 vs 0.1439
Element-wise exact probabilities	Spearman ρ = 0.997; FDR discoveries 0 vs 0
Two-axis PCA configuration	Procrustes similarity = 0.835
All-sample Aitchison distances	Spearman ρ = 0.937
Ward cophenetic distances	Spearman ρ = 0.836

Discussion

The dominant Ca–Si–Fe–Al–K matrix and the absence of a single medium-wide ordination axis produced a pattern consistent with local provenance, hydraulic sorting and bank–channel exchange.

Carbonate and silicate phases dominate suspended material in the Mesopotamian Plain, while downstream changes in sand mineralogy and grain size can alter the relative abundance of element-bearing minerals [1, 2]. Because mineralogy and grain size were not measured here, these processes remain plausible interpretations rather than demonstrated controls.

Channel curvature, point-bar deposition, revetment, bank failure, local drains and agricultural return flow can all alter the material exchanged between bank and channel. Riverbank erodibility and stability studies in Baghdad provide a physical mechanism for such redistribution [6, 16]. The non-monotonic sequence is compatible with reach-specific sediment storage and remobilization, although the present data cannot discriminate among geological, hydraulic and local anthropogenic explanations.

Median total-XRF Cr concentrations were 220.0, 278.0 and 275.0 mg kg⁻¹ in channel sediment, right-bank soil and left-bank soil, respectively; corresponding Ni medians were 36.2, 115.1 and 126.7 mg kg⁻¹. These values are consistent with earlier Iraqi soil and sediment studies [9–11]. Mafic minerals, heavy-mineral fractions and grain-size sorting can elevate these elements without an exclusively anthropogenic source, while local agriculture, wastewater and oil-related activities may also contribute at individual reaches [5, 7, 8]. Without mineral-specific extractions, oxidation-state measurements or source tracers, the concentrations are interpreted as total-element profiles rather than as evidence of toxic contamination.

Cd, Hg, Ag, Te and Tl occur near the low end of the XRF screening range. Their concentrations should not be used for regulatory or health-risk calculations without element-specific detection limits and independent digestion-based confirmation. Total abundance also differs from mobility and bioavailability, which depend on pH, carbonate, organic matter, redox conditions and particle size.

The analytical design avoids two common sources of overstatement. First, CLR coordinates remove the false independence implied by closed percentages. Second, restricted permutations preserve the seven matched reaches; an unrestricted analysis would inflate the nominal sample size by ignoring that the three media share local geology and hydrology. FDR correction further prevents isolated p values among 41 elements from becoming a pollution narrative. The combination of effect sizes, exact element-wise inference, Monte Carlo multivariate permutation and Aitchison distance provides a more transparent interpretation than raw correlations alone.

The source workbook contained four major-element entries whose scale was reconciled with the reported sample totals and documented individually in Table 1. Restricting reconciliation to these entries preserved all statistically extreme trace values. Results from the unmodified transcription and reconciled dataset are reported together, making the influence of scale reconciliation explicit. Trace-element extremes were retained because local mineral grains or point inputs can be real; their interpretation remains screening-level.

The sampling intensity and matched structure were defined by the cross-sectional river-corridor survey. Formal inference therefore concerns patterns recurring across the seven surveyed reaches, while reach

centroids serve only as regional locators. The analytical scope is comparison of total-element profiles among channel sediment and the two banks; it does not extend to spatial interpolation, causal source apportionment, equivalence testing or ecological-risk classification. The matched descriptive statistics, exact element-wise tests and restricted multivariate permutation align the analysis with that stated scope.

Conclusions

This exploratory 7×3 river-corridor survey linked channel sediment with both Tigris banks across 21 samples and 41 XRF-screened elements. The CLR–Aitchison framework and within-reach label permutation provided insufficient evidence of a consistent medium effect across the seven surveyed reaches; this result does not establish equivalence or absence of local differences. Ca, Si and Fe dominated the measured matrix, while Cr and Ni occurred at comparatively high total-XRF concentrations that require mineralogical and bioavailability confirmation before environmental interpretation. Exact element-wise tests with FDR control prevented isolated contrasts from being overstated. The findings justify more intensive reach-specific monitoring with within-reach field replication, verified coordinates, river-kilometre distances, grain-size and soil-chemistry covariates, and confirmatory digestion-based analysis.

Declarations

Acknowledgements The author acknowledges the laboratory staff who supported XRF analysis.

Author contributions R.S.M.: conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing—original draft, and writing—review and editing.

Funding No funding was received for this study.

Data availability The raw transcription, reconciled analysis matrix, complete element-wise and pairwise test results, CLR-PCA scores and loadings, Aitchison distances, metadata and analysis code are available from the corresponding author on reasonable request.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The author declares no competing interests.

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Figures

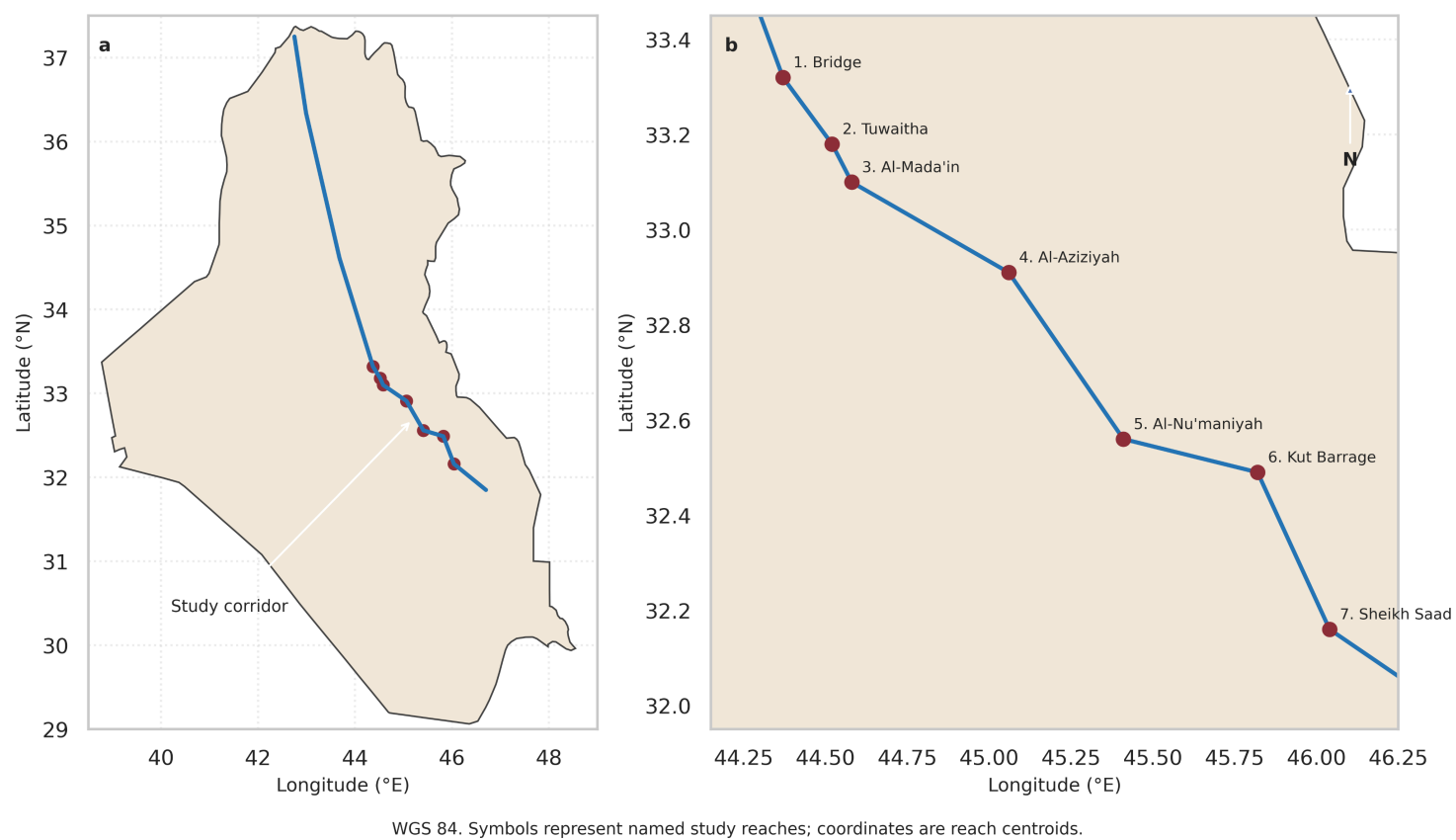


Figure 1

Location of the seven matched Tigris River study reaches sampled in summer 2024. WGS 84; symbols represent reach centroids

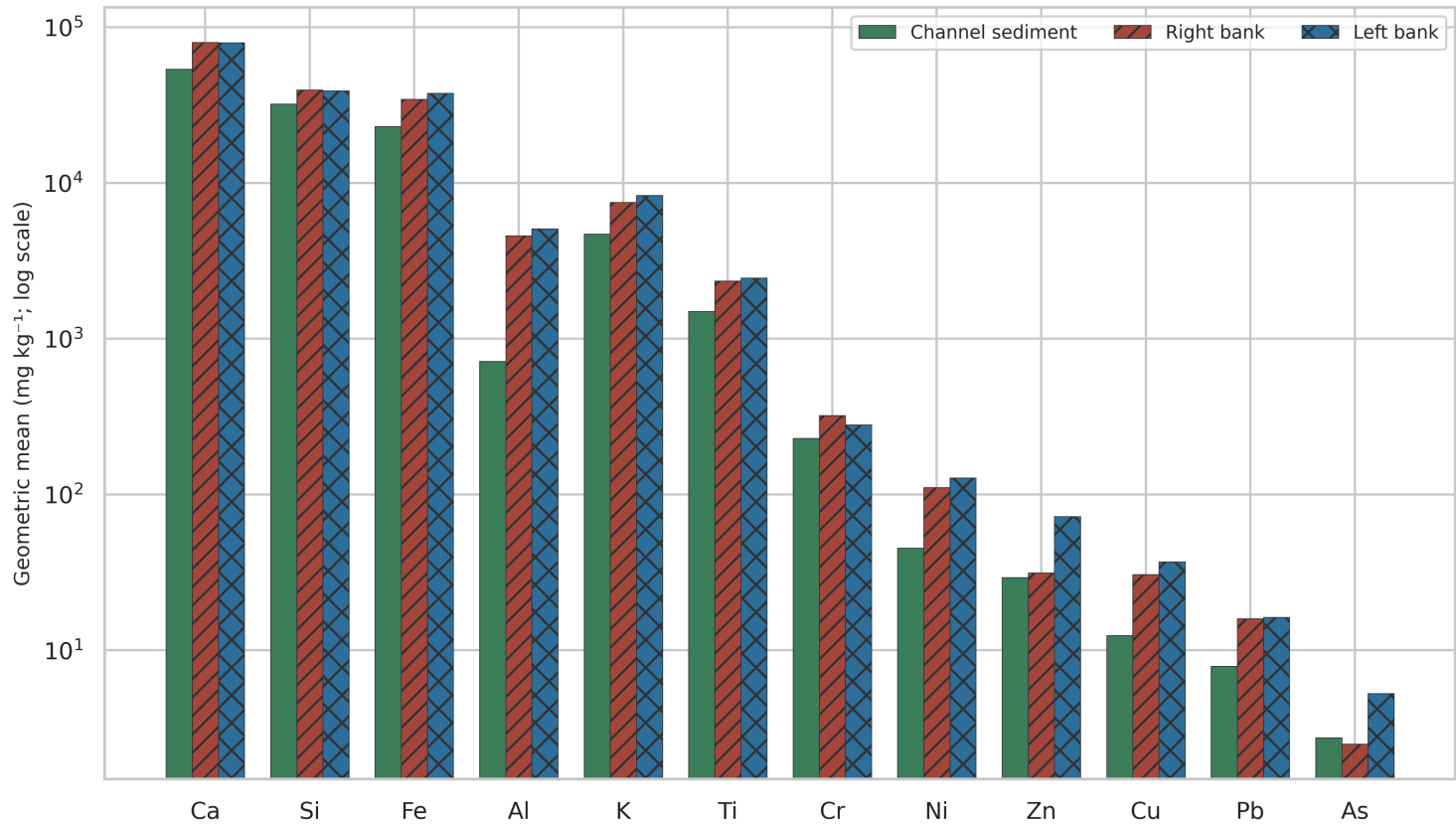


Figure 2

Geometric-mean concentrations for major and selected trace elements. The logarithmic axis accommodates the multi-order concentration range

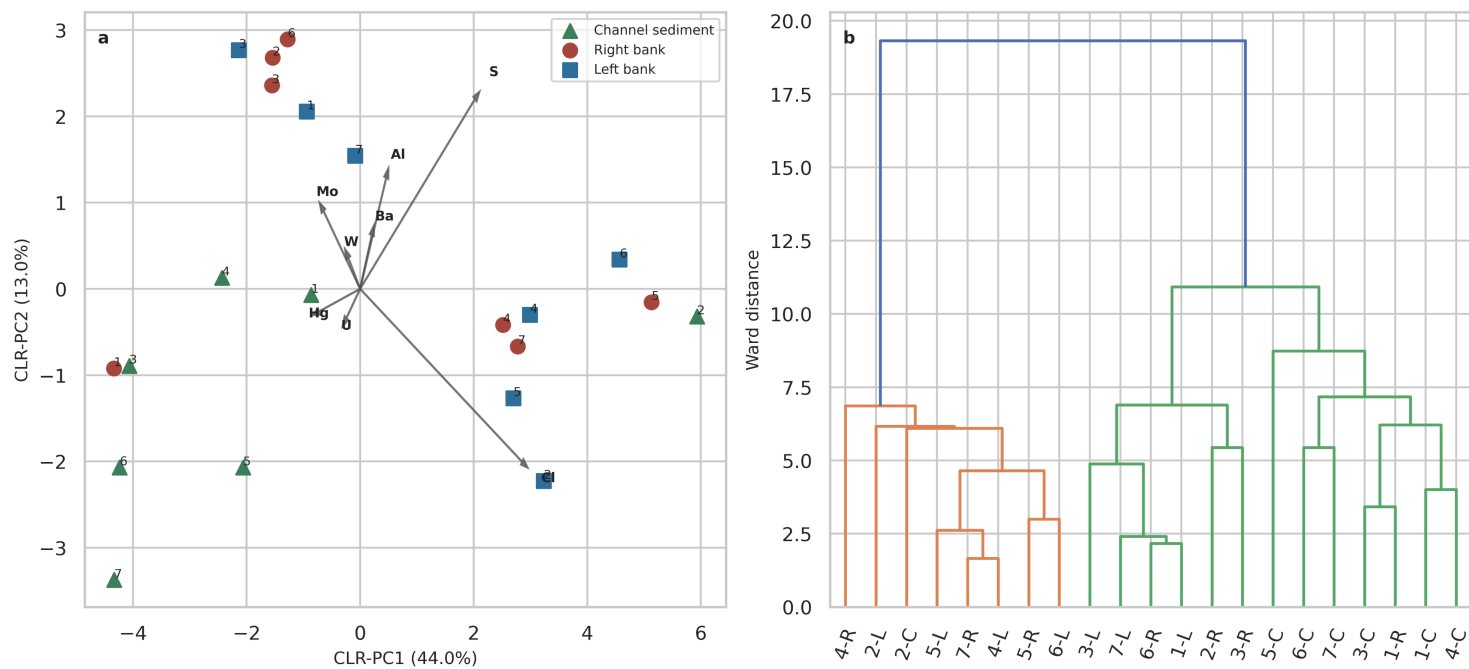


Figure 3

CLR-based multivariate structure: (a) PCA biplot; (b) SciPy Ward-linkage clustering using Euclidean distance in CLR space. Numbers identify reaches in upstream-to-downstream order; C, R and L denote channel sediment, right bank and left bank

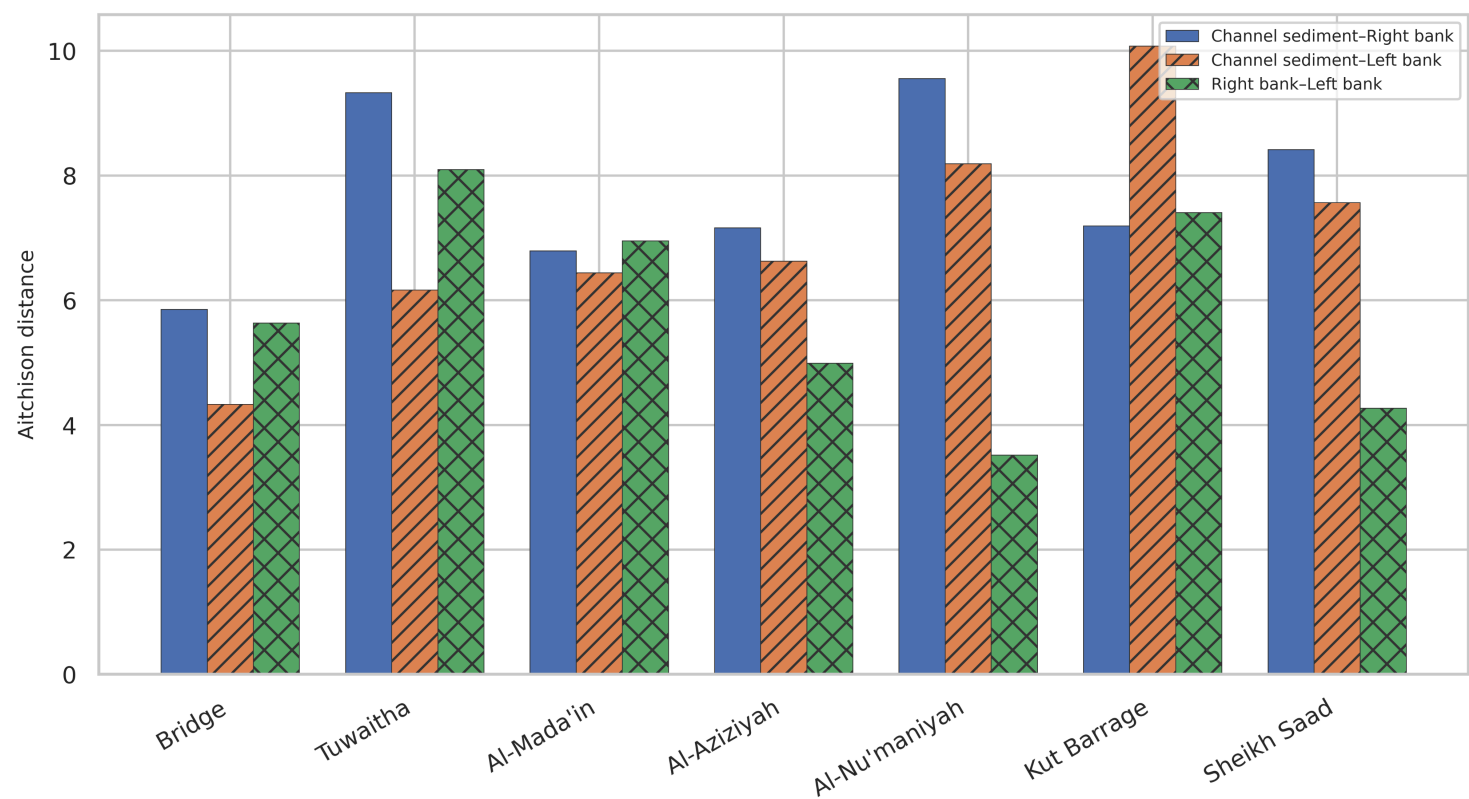


Figure 4
Matched Aitchison distances among channel sediment and the two banks at each reach

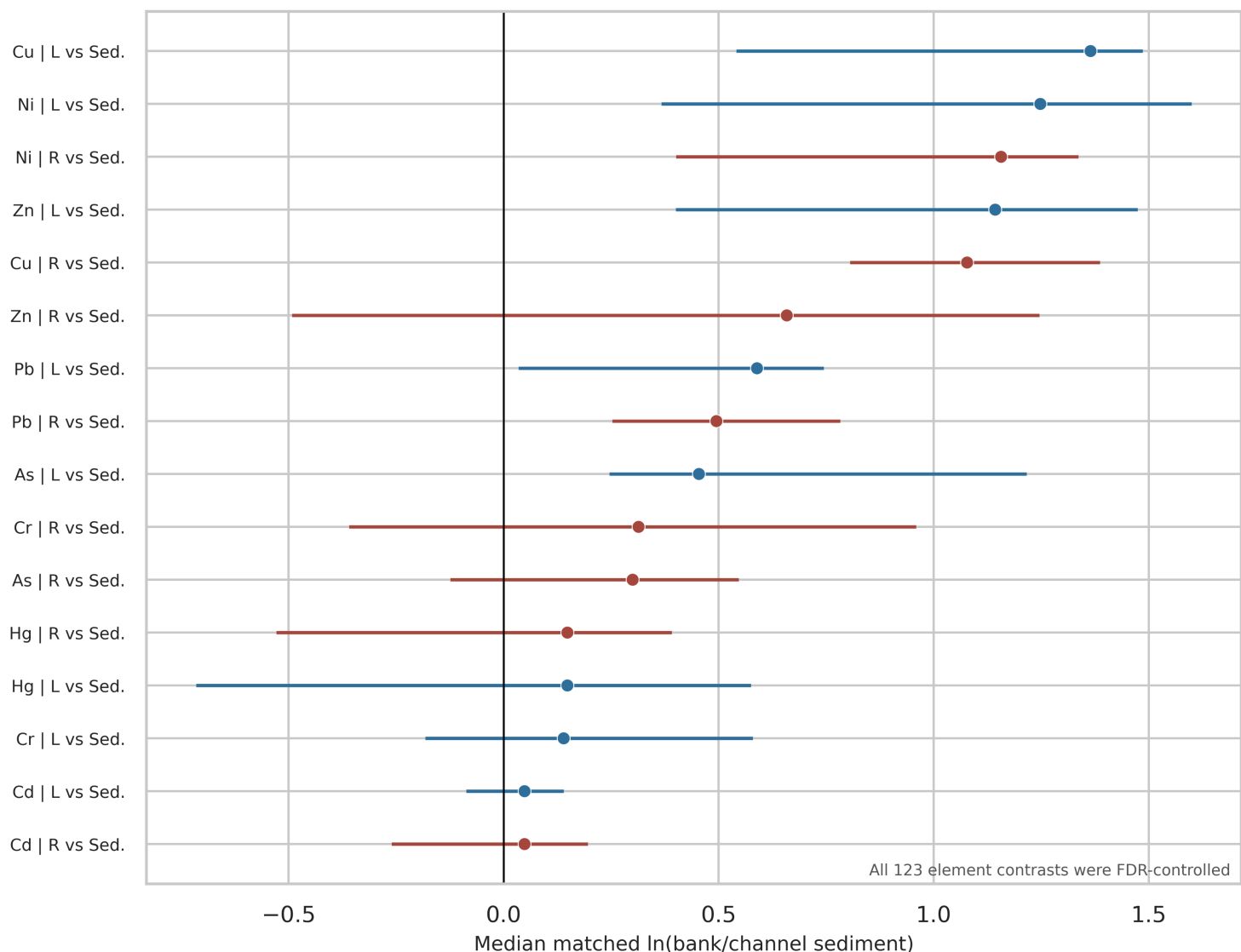


Figure 5

Median matched bank-to-channel log-ratio effects with exploratory percentile-bootstrap 95% intervals (10,000 reach-level resamples; $n = 7$). Positive values indicate a larger bank concentration. Intervals are unadjusted summaries; FDR control applies to the 123 permutation tests, not to these intervals

Supplementary Files

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