

Estuarine mixing governs spatiotemporal partitioning of potentially toxic elements between coastal waters and sediments in the western Indian Ocean

Jane Moraa Nyamora

janenyamora8@gmail.com

Kenya Marine and Fisheries Research Institute <https://orcid.org/0000-0002-2325-4172>

James Njiru

Kisii University

Albert Getabu

Kisii University

Kobingi Nyakeya

Kenya Marine and Fisheries Research Institute

Research Article

Keywords: trace metals, salinity gradient, surface sediment, tropical estuary, monsoon, western Indian Ocean, Kenya coast

Posted Date: October 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11265230/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Potentially toxic elements in tropical estuaries are controlled by the interaction of catchment inputs, tidal exchange, particle settling and hydrochemical gradients, yet process-based evidence remains limited for the western Indian Ocean. This study quantified arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), mercury (Hg), manganese (Mn), nickel (Ni), and lead (Pb) in surface water and the active sediment layer at Gazi, Mkunguni, Shimoni and Vanga on the South Coast of Kenya over 12 months (March 2022-February 2023) and tested whether estuarine physiochemistry explained the observed spatial-temporal patterns. Water-quality variables included temperature, dissolved oxygen, conductivity, total dissolved solids, salinity, pH, phosphate, nitrate and ammonia. Metals were determined after acid preparation using ICP-OES. Spatial and temporal effects were evaluated using one- and two-way ANOVA, and standardized multiple regression was used to identify hydrochemical controls. All ten metals differed among stations in both water and sediments ($p < 0.01$), whereas month effects were generally weak. Gazi recorded the largest station-month maxima for most elements, including 80.6 micrograms/L Fe and 22.9 micrograms/L Mn in water and 30,200 mg/kg Fe and 905 mg/kg Mn in sediment; Shimoni usually recorded the minima. Chromium was the only element with a significant station-by-month interaction in both matrices. Salinity was negatively correlated with every sediment metal ($r = -0.54$ to -0.87), with the strongest relationships for Mn, Co, Fe, Cd and Pb. Multivariable models explained 26% of Cr to 75% of Mn variability, and salinity remained the dominant standardized predictor for every sediment metal ($p < 0.001$). The results indicate that freshwater influence, ionic-strength gradients and depositional retention produced persistent site-specific sediment reservoirs while short-lived monthly signals were damped at the coast-wide scale. Monitoring programs should therefore pair water and sediment measurements, stratify sampling by estuarine mixing regime and target low-salinity, fine-sediment retention zones rather than relying on single-season water surveys.

Highlights

- Spatial effects dominated temporal variability in water and surface sediments.
- Gazi was the principal multi-element hotspot; Shimoni was consistently lower.
- Salinity correlated negatively with every sediment metal ($r = -0.54$ to -0.87).
- Hydrochemical models explained 26-75% of sediment-metal variability.
- Water-only monitoring would miss persistent sediment contamination reservoirs.

1. Introduction

Coastal estuaries are simultaneously productive ecosystems, pollutant conduits and geochemical reactors. Their shallow waters, strong land-sea connectivity and high rates of particle deposition support fisheries, mangroves and seagrass habitats, but also concentrate contaminants delivered by rivers,

stormwater, wastewater, vessel activity and shoreline development. Potentially toxic elements are particularly important because they do not degrade, can shift among dissolved, particulate and sediment-bound phases, and may remain available long after an input event has ended (Du Laing et al., 2009; Ali et al., 2022; El-Sharkawy et al., 2025). Sediments therefore function both as an archive of cumulative loading and as a secondary source when changes in salinity, pH, oxygen or hydrodynamic energy promote desorption, dissolution or resuspension (Atkinson et al., 2007; Dellapenna et al., 2020; Zafra-Mejia and Rondon-Quintana, 2025).

The environmental meaning of measured concentration depends strongly on matrix and process. Dissolved concentrations often capture recent loading but may fall rapidly through dilution, complexation or adsorption. Surface sediments integrate repeated inputs and retain metals on clay minerals, organic matter, carbonates and Fe-Mn oxides. Modern studies have shown that sedimentary organic matter can become a temporary sink for anthropogenic Pb and Zn, while benthic organisms can accumulate metals from deposits that appear disconnected from the overlying water column (Ahmad et al., 2024; Miess et al., 2025). Consequently, a water-only survey may indicate acceptable short-term conditions while overlooking a persistent exposure reservoir at the sediment-water interface.

Estuarine mixing is a major control on this partitioning. Increasing salinity changes ionic strength, competitive sorption, chloride complexation and flocculation; freshwater inflow alters suspended-solids delivery and residence time; and oxygen-pH oscillations regulate the stability of redox-sensitive Fe and Mn phases. In the Modaomen Estuary, water-density stratification associated with salinity structured the partitioning of metals between water and sediment (Jia et al., 2021). Experimental evidence likewise shows that salinity, pH, dissolved oxygen and disturbance can alter release and sequestration from contaminated marine sediments (Atkinson et al., 2007). These controls are not uniform across elements: Cr may respond to redox transformations and source-specific pulses, whereas Fe, Mn, Pb, Cd and Ni commonly track particle deposition and oxide cycling.

Temporal variability is superimposed on this spatial geochemistry. Floods, tropical storms and monsoon runoff transport fresh particulate matter and can erode previously deposited material. Dellapenna et al. (2020) demonstrated that cyclone flooding redistributed mercury-contaminated sediment across an urban estuary, while Tao et al. (2021) showed that sediment disturbance altered both metal concentrations and benthic exposure. Recent Environmental Pollution studies similarly emphasize that runoff, resuspension and sediment storage create exposure patterns that are not captured by static source-distance models (Guo et al., 2023; Niu et al., 2023; Zafra-Mejia and Rondon-Quintana, 2025). Thus, the strongest seasonal effect may occur not when total loading is highest, but when hydrodynamic conditions increase mobility or ecological contact.

Tropical western Indian Ocean estuaries are especially sensitive because the Southeast and Northeast monsoons reorganize rainfall, river discharge, current velocity, turbidity and water residence time. Along the Kenyan coast, artisanal fisheries and mangrove lined bays coexist with agricultural runoff, untreated domestic waste, tourism, vessel maintenance and expanding port activity. Earlier work in Mombasa

documented Cd and Pb in water, sediments and fish, confirming that coastal metal contamination is not new (Mwashote, 2003). However, most regional studies have been spatial snapshots, have focused on one environmental matrix, or have interpreted concentration without quantitatively linking them to hydrochemical gradients.

The distinction between a site-specific concentration survey and a process-based assessment matters for understanding estuarine contamination. Testing the joint influence of sources, transport and retention can identify whether spatial or temporal forcing dominates and which hydrochemical variables explain metal storage. Multivariate signatures, runoff gradients, sediment source analysis and trophic transfer have helped resolve these mechanisms in other coastal settings (Guo et al., 2023; Niu et al., 2023; Parikh et al., 2024; Saidon et al., 2024; Meschede et al., 2024; Li et al., 2025). Similar analysis along the South Coast of Kenya can establish whether these processes operate under monsoon forcing and carbonate-rich sediment conditions.

The South Coast of Kenya provides an informative natural gradient. Gazi is a sheltered mangrove-fringed bay with catchment and shoreline inputs; Mkunguni represents an intermediate artisanal fishing setting; Shimoni combines stronger marine exchange with port and tourism activity; and Vanga receives estuarine influence near the Kenya-Tanzania border. These sites differ in flushing, depositional environment and potential source mixtures, permitting explicit tests of spatial retention versus coast-wide seasonality.

This study therefore evaluated the spatiotemporal distribution and hydrochemical controls of As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni and Pb in surface water and sediments at four South Coast stations. We tested three hypotheses: (1) station effects would exceed month effects because local source and retention conditions differ among estuaries; (2) sediments would show stronger and more persistent spatial structuring than water; and (3) salinity and related ionic gradients would be the principal predictors of sediment-metal variability. By linking monthly environmental measurements to standardized regression models, the study provides a process-based interpretation of contaminant storage in a tropical western Indian Ocean coastline and identifies monitoring designs capable of detecting both mobile and stored pollution signals.

2. Materials and methods

2.1 Study area and sampling framework

2.1. Study area

The study was conducted in Kwale County on the South Coast of Kenya at Gazi (-4.42873 S, 39.51158 E), Mkunguni (-4.47304 S, 39.49077 E), Shimoni (-4.64759 S, 39.38073 E) and Vanga (-4.66026 S, 39.21985 E). The Kenyan coast is shaped by a strong seasonal monsoon cycle, with the Southeast Monsoon generally occurring from April to September and the Northeast Monsoon from October to March. These seasonal shifts influence rainfall, river discharge, terrestrial runoff, currents, wave activity and water-

column mixing, creating noticeable changes in coastal environmental conditions throughout the year (McClanahan, 1988; Obura, 2001). The coast also experiences mixed semi-diurnal tides and supports a diverse mosaic of mangrove forests, seagrass meadows, coral reefs and nearshore habitats, each contributing differently to the functioning and productivity of coastal ecosystems.

Along the South Coast, these environmental conditions vary considerably among locations. Gazi is strongly influenced by mangrove and estuarine processes, while Mkunguni represents a more open nearshore setting. Shimoni is influenced by fishing, tourism and vessel activity, whereas Vanga lies close to the Kenya–Tanzania border and is influenced by the Umba River and associated coastal processes. Together, these sites capture a range of environmental and human influences that may affect the distribution and accumulation of metals in coastal sediments. These differences among the sites help to explain how metal contamination varies along Kenya’s South Coast.

Environmental sampling was carried out over 12 consecutive months, from March 2022 to February 2023, using a balanced station-by-month design. At each station, surface-water and intertidal surface-sediment samples were collected from matched, georeferenced locations during each monthly sampling event. This consistent sampling approach provided a comparable water–sediment dataset across the four stations and throughout the study period. The 12-month period was selected to capture the full environmental time series required for assessing spatial and temporal patterns in metal concentrations and their relationships with hydrochemical conditions.

2.2 Water and sediment collection

All sampling equipment was cleaned with nitric acid and rinsed with deionized water before use. Surface water was collected below the air-water interface into pre-cleaned high-density polyethylene containers while facing the current. Samples were capped immediately, transported on ice and stored frozen until analysis. In situ measurements were obtained before disturbance of the sampling point.

Surface sediments were collected from the active depositional zone at each sampling station using a stainless-steel corer inserted to approximately 10 cm below the sediment–water interface. Three replicate samples were collected at each station during every sampling event to capture local variation in sediment conditions. The samples were placed in pre-cleaned, acid-washed polyethylene bags, transported in cooled containers, and stored at – 20°C until analysis. The 0–10 cm surface layer was selected because it is the part of the sediment most directly exposed to the overlying water and involved in sediment–water interactions, contaminant exchange, and potential resuspension processes (U.S. EPA, 2025; Nario et al., 2025).

2.3 Physicochemical measurements

Temperature, pH, salinity, electrical conductivity, total dissolved solids (TDS), and dissolved oxygen (DO) were measured at each sampling station using calibrated YSI ProDSS multiparameter meters. The meters were calibrated before each sampling day in accordance with the manufacturer’s recommended

procedures. Water samples were also collected for phosphate, nitrate, and ammonia analysis using automated flow analysis following standard analytical procedures (APHA, AWWA, & WEF, 2017). The hydro-chemical measurements were summarized by station and month and used to describe the environmental conditions associated with the observed patterns of metal contamination in the sediments.

2.4 Digestion, metal quantification and quality control

All laboratory vessels were thoroughly cleaned with detergent, rinsed with water, soaked in 5% nitric acid for at least 24 h, and then rinsed with ultrapure water to minimize possible metal contamination. Sediment samples were digested using nitric acid and hydrogen peroxide under microwave-assisted heating and diluted to a fixed final volume following EPA Method 3051A (USEPA, 2007). Arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), and lead (Pb) were determined by inductively coupled plasma–optical emission spectrometry (ICP-OES) using a PerkinElmer Optima 4300 DV. Appropriate analytical wavelengths were selected for each element, and calibration was carried out using certified multielement standards. Procedural blanks, replicate analyses, and recovery checks were included throughout the analysis to monitor contamination, precision, and the reliability of the measurements.

2.5 Statistical analysis

Concentrations were summarized by station and month. One-way ANOVA tested station and month effects separately for each element, and two-way ANOVA partitioned station, month and station-by-month interaction effects. Where model assumptions were not met, equivalent rank-based tests and appropriate post-hoc comparisons were used. Statistical significance was evaluated at $\alpha = 0.05$.

Pearson correlations quantified bivariate associations between hydro-chemical variables and sediment metals. Multiple linear regression models were then fitted for each sediment metal using temperature, dissolved oxygen, salinity, pH, phosphate, nitrate and ammonia as candidate predictors. Variables were standardized before modeling so that coefficient magnitudes were comparable, and heteroscedasticity-consistent standard errors were used where indicated. Adjusted R-squared was used to compare explanatory power. The analysis was conducted in R and Python.

Table 1
Sampling design and analytical framework.

Matrix	Design	Sampling layer	Variables	Interpretive role
Water	4 stations x 12 months	Surface layer	As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb	Short-term dissolved/mobile signal
Sediment	4 stations x 12 months x 3 field replicates	Upper ~ 10 cm	Same 10 elements	Depositional reservoir and remobilization potential
Hydrochemistry	Matched station-month observations	In situ + laboratory	Temperature, DO, conductivity, TDS, salinity, pH, PO ₄ , NO ₃ , NH ₃	Mechanistic predictors

3. Results

3.1 Spatial structure of dissolved metals

All ten dissolved elements differed significantly among stations. Station F values ranged from 4.35 for Cr to 24.88 for Mn, with $p = 0.006$ for Cr and $p < 0.001$ for the remaining elements. Gazi produced the largest station-month maximum for every dissolved element; the maxima included 1.89 micrograms/L As, 0.13 micrograms/L Cd, 2.20 micrograms/L Cr, 80.6 micrograms/L Fe, 22.9 micrograms/L Mn and 1.23 micrograms/L Pb. Shimoni produced most minimum, including 1.36 micrograms/L As, 1.36 micrograms/L Cr, 62.0 micrograms/L Fe and 17.8 micrograms/L Mn. The resulting spatial hierarchy was therefore Gazi as the principal multi-element hotspot, Vanga and Mkunguni as intermediate sites, and Shimoni as the generally lower-concentration site.

3.2 Weak coast-wide month effects but element-specific interactions

When observations were pooled across stations, none of the ten dissolved metals showed a significant one-way month effect (all $p > 0.098$). The two-way models confirmed that station was the dominant term. Chromium was the exception: month ($F = 2.03$, $p = 0.033$) and the station-by-month interaction ($F = 1.61$, $p = 0.038$) were significant, indicating asynchronous Cr mobilization among sites. Other elements showed visually distinct peaks, but those peaks did not occur at the same stations or months and therefore did not form a coherent coast-wide seasonal signal.

3.3 Sediments amplified the spatial contamination signal

All sediment metals differed strongly among stations (all $p < 0.001$). The largest spatial contrasts occurred for Mn ($F = 34.65$), Fe ($F = 28.05$), Pb ($F = 22.44$) and Co ($F = 22.35$). Gazi again recorded the maximum concentrations for every element, including 16.8 mg/kg As, 0.39 mg/kg Cd, 89.7 mg/kg Cr,

58.3 mg/kg Cu, 30,200 mg/kg Fe, 905 mg/kg Mn and 38.1 mg/kg Pb. In comparison, Shimoni recorded the minimum concentrations across the sampling sites. Month was non-significant for all sediment metals, but Cr had a significant station-by-month interaction ($F = 1.69$, $p = 0.025$). Sediments therefore preserved a strong local source-retention signature despite moderate descriptive month-to-month fluctuation.

Table 2

Summary of two-way ANOVA terms. A dash indicates that the corresponding table did not report a Cu interaction row.

Metal	Water station p	Water month p	Water interaction p	Sediment station p	Sediment month p	Sediment interaction p
As	< 0.001	0.320	0.723	< 0.001	0.410	0.218
Cd	< 0.001	0.303	0.550	< 0.001	0.383	0.707
Co	< 0.001	0.989	0.790	< 0.001	0.781	0.956
Cr	0.002	0.033	0.038	< 0.001	0.417	0.025
Cu	< 0.001	0.614	-	< 0.001	0.511	0.127
Fe	< 0.001	0.741	0.359	< 0.001	0.308	0.451
Hg	< 0.001	0.339	0.490	< 0.001	0.340	0.196
Mn	< 0.001	0.820	0.499	< 0.001	0.738	0.884
Ni	< 0.001	0.661	0.336	< 0.001	0.974	0.195
Pb	< 0.001	0.106	0.303	< 0.001	0.581	0.264

3.4 Salinity dominated sediment-metal variability

Salinity was negatively correlated with every sediment metal, from $r = -0.54$ for Cr to $r = -0.87$ for Mn. The strongest salinity associations were observed for Mn ($r = -0.87$), Co (-0.80), Fe (-0.79), Cd (-0.72) and Pb (-0.72), all $p < 0.001$. Conductivity and TDS showed parallel negative patterns. Conductivity correlations reached -0.73 for Mn, -0.69 for Fe, -0.67 for Ni and -0.66 for Pb, whereas TDS correlations reached -0.76 for Mn, -0.73 for Co and -0.69 for Pb.

Regression results reinforced the bivariate pattern. Adjusted R-squared ranged from 0.26 for Cr to 0.75 for Mn, and salinity was the largest standardized coefficient in every model (all $p < 0.001$). Particularly strong models were obtained for Mn (adjusted R-squared = 0.75; beta salinity = -0.89), Co (0.62; beta = -0.83), Fe (0.60; beta = -0.79), Pb (0.53; beta = -0.70) and Cd (0.52; beta = -0.69). Secondary nutrient, temperature, pH and oxygen coefficients were smaller and mostly non-significant.

Table 3
Multiple regression models for sediment metal concentrations.

Sediment metal	Adjusted R2	Standardized salinity beta (p)	Next-largest reported predictor beta (p)
As	0.42	-0.59 (< 0.001)	NH3: -0.21 (0.038)
Cd	0.52	-0.69 (< 0.001)	NH3: 0.25 (0.060)
Co	0.62	-0.83 (< 0.001)	NO3: -0.13 (0.241)
Cr	0.26	-0.51 (< 0.001)	NH3: -0.22 (0.055)
Cu	0.32	-0.63 (< 0.001)	DO: 0.26 (0.131)
Fe	0.60	-0.79 (< 0.001)	Temperature: 0.17 (0.067)
Hg	0.42	-0.64 (< 0.001)	DO: 0.14 (0.291)
Mn	0.75	-0.89 (< 0.001)	pH: -0.10 (0.217)
Ni	0.40	-0.70 (< 0.001)	NO3: -0.17 (0.224)
Pb	0.53	-0.70 (< 0.001)	NO3: 0.19 (0.185)

4. Discussion

The dominant result was the consistency of the station effect across all ten elements and both matrices. This rejects an interpretation based on uniform regional forcing. Instead, each site behaved as a distinct hydro-sedimentary exposure unit in which source intensity, flushing, particle trapping and sediment composition combined to determine metal concentration. Gazi was repeatedly the highest station and Shimoni the lowest, while Vanga and Mkunguni occupied intermediate positions. The pattern is compatible with a sheltered mangrove-estuary environment in which runoff-derived particles and organic matter are retained, rather than with a simple north-south or distance-from-city gradient.

This distinction is important because source proximity alone rarely predicts estuarine contamination. Metals delivered from diffuse agriculture, settlements and vessel activity may travel on suspended particles before settling in low-energy channels. Guo et al. (2023) demonstrated that coastal sediments integrate toxic metals with microbial and resistance-gene signatures, while Niu et al. (2023) showed that urban industrial influence is strongly mediated by the receiving sediment system. In the South Coast dataset, the coincidence of elevated Fe, Mn, Co, Ni and Pb at Gazi suggests that particle-associated deposition and oxide-rich phases were central to retention. Fe and Mn are major sediment constituents, but their oxides also sorb other trace elements; their spatial pattern therefore helps explain the behavior of anthropogenic metals rather than representing only natural geology.

The water-sediment contrast strengthens this interpretation. Water showed statistically significant station differences, but the magnitude and persistence of the sediment signal were greater. Dissolved

concentrations are rapidly modified by tidal dilution, mixing and adsorption. Sediments accumulate multiple pulses and preserve the integrated history of inputs. Ahmad et al. (2024) recently showed that autochthonous organic matter can be a major, potentially reversible metal sink, while Miess et al. (2025) demonstrated that benthic fauna can accumulate metals from deep sediment reservoirs even where the water column underrepresents exposure. The South Coast findings extend this logic to tropical mangrove-estuary settings: sediment was not a passive endpoint but the main environmental memory of contamination.

The management implication is that apparent water-column improvement cannot be treated as evidence of ecosystem recovery. Sediment-bound metals can be re-exposed by tidal scouring, storms, burrowing organisms, dredging and fishing disturbance. Zafra-Mejia and Rondon-Quintana (2025) emphasized the potential availability of resuspended metals after runoff, and Dellapenna et al. (2020) documented large-scale redistribution of mercury-contaminated sediment by flooding. At South Coast landing areas, much smaller but frequent disturbances may repeatedly renew contact between contaminated particles, benthic prey and fish gills. A regulatory program that samples water alone would therefore be biased toward the most transient compartment.

The absence of significant pooled month effects for most metals does not imply that seasonality was irrelevant. The interaction plots showed asynchronous station-specific peaks. A rainfall or runoff event may increase contamination at one creek while stronger flushing reduces concentration at another. Pooling stations can therefore cancel opposite responses. The significant Cr interaction in both matrices is a clear example: Cr changed through time, but the direction and magnitude depended on station.

Chromium is particularly sensitive to source form and redox chemistry. Its dissolved and particulate fractions can respond differently to oxygenation, pH and organic matter, and local inputs from paints, metal surfaces or catchment soils may be episodic. The repeated station-by-month effect suggests that Cr should be monitored with speciation or sequential extraction rather than interpreted solely as total concentration. More broadly, the result shows why a binary wet-season/dry-season comparison can be insufficient. Monsoon labels describe regional atmospheric forcing, but contaminant response is mediated by local residence time, freshwater pathways and sediment disturbance.

The weak main month effect is also consistent with the long residence of metals in sediments. Once particles settle, the sediment inventory changes more slowly than rainfall or surface-water chemistry. Even a substantial input pulse may represent a small addition to an existing stock, whereas resuspension may alter ecological availability without changing total sediment concentration. Ciszewski and Grygar (2016) and Tao et al. (2021) similarly noted that transport events can reorganize exposure while producing limited changes in bulk concentration. Future studies should therefore complement total metals with porewater, labile-fraction or diffusive-gradient measurements that respond more directly to short-term geochemical change.

The uniformly negative salinity-metal relationships were the clearest mechanistic signal. Salinity explained more variation than temperature, oxygen, pH or nutrients and remained significant in all ten

standardized models. In this setting, low salinity likely represented a combined freshwater and particulate-input signal: periods or locations with stronger catchment influence delivered more fine sediment and associated metals, while marine-dominated conditions promoted dilution and different complexation behavior. Because conductivity and TDS tracked the same gradient, the interpretation is not based on a single instrument variable but on a coherent ionic-mixing axis.

Jia et al. (2021) found that salinity-associated density stratification-controlled metal partitioning in a large estuary, and Atkinson et al. (2007) experimentally demonstrated that salinity can alter release and sequestration from marine sediments. The direction of a salinity effect is context dependent. Increasing chloride may enhance complexation of some metals, while higher ionic strength can promote flocculation or competition for sorption sites. In the South Coast data, the negative coefficients imply that the dominant field-scale effect was catchment loading and freshwater-associated deposition rather than simple salt-induced desorption.

The element-specific model strengths are geochemically plausible. Mn, Co and Fe had the highest explained variance because they are closely linked to oxide phases and depositional processes. Pb and Cd also responded strongly, consistent with their affinity for particles and organic matter. Cr had the weakest model, reinforcing the interpretation that redox state, source form or episodic local inputs introduced additional variability. Zhao et al. (2024) similarly concluded that pH, temperature and salinity jointly affect metal mobility but that responses differ among elements and sediment matrices.

Salinity should not be interpreted as a direct contaminant. Rather, it serves as an integrated environmental indicator that reflects the combined effects of freshwater inflow, seawater dilution, ionic strength, and water residence time. Consequently, variations in salinity provide valuable insight into the hydrological conditions that influence the transport, distribution, and bioavailability of contaminants within the aquatic environment. Its value is practical: low-salinity station-months can be used to trigger intensified sediment and biota sampling. Parikh et al. (2024) showed that salinity and agricultural runoff jointly structured coastal fish assemblages, illustrating how an estuarine mixing variable can link catchment pressure to biological response. In South Coast Kenya, a salinity-stratified design would be more informative than fixed quarterly sampling because it would target the conditions under which metal-rich material is most likely to enter and settle.

The findings support a tiered monitoring framework. The first tier should measure salinity, conductivity, TDS, oxygen and turbidity continuously or at high frequency. The second should quantify total and labile metals in surface sediment at sentinel depositional zones. The third should sample benthic prey and fish tissues when hydrochemical thresholds or disturbance events indicate increased exposure potential. This design recognizes that environmental concentration and biological uptake are related but not interchangeable.

Recent pollution research increasingly combines chemical, ecological and human-health endpoints. Saidon et al. (2024) emphasized that trophic transfer is metal specific, and Meschede et al. (2024) demonstrated the need to connect measured element concentrations with realistic dietary exposure.

Although the present paper focuses on environmental partitioning, its hydrochemical results provide the process basis for those later pathways. Persistent sediment reservoirs at Gazi and Vanga can sustain exposure even when water concentrations are low, while weak coast-wide month effects mean that local event-based sampling is necessary.

The study also has implications for pollution-source control. Catchment runoff, wastewater, boat maintenance and shoreline disturbance require different interventions. The multimetal pattern cannot uniquely apportion sources, so source tracing should be added using Pb isotopes, enrichment factors, sediment mineralogy or receptor models. Environmental Pollution studies such as Guo et al. (2023), Niu et al. (2023) and Li et al. (2025) illustrate how source attribution can transform concentration data into actionable regulation. For Kenya, this would allow managers to distinguish geogenic Fe-Mn-rich material from anthropogenic Pb, Cd, Cu, Ni or Cr contributions.

The observed salinity response also needs to be interpreted within the mineralogical setting of a tropical coast dominated by coral-derived carbonates, mangrove detritus and seasonally delivered terrigenous particles. Carbonate minerals can buffer pH and provide sorption surfaces, while mangrove organic matter supplies functional groups that bind metals and create oxygen gradients during decomposition. These properties can retain contaminants under one set of conditions and release them when ionic strength, redox potential or particle disturbance changes. Atkinson et al. (2007) showed experimentally that overlying water salinity, pH, dissolved oxygen and disturbance can alter the release and sequestration of metals from contaminated marine sediment. Du Laing et al. (2009) similarly emphasized that metal mobility in wetlands emerges from interactions among sulfides, organic matter, iron-manganese oxides and changing redox conditions rather than from total concentration alone.

This framework explains why Fe, Mn and Co responded strongly to the hydro-chemical gradient. Fe and Mn oxides are not merely co-occurring elements; they are reactive carriers that scavenge Pb, Cd, Cr, Cu and Ni from the water column. Under reducing conditions, oxide dissolution can release sorbed metals, whereas re-oxidation near the sediment-water interface can create fresh sorption surfaces. The high adjusted R-squared values for Mn, Co and Fe therefore point to coordinated redox-sensitive mineral cycling. The weaker Cr model is also instructive because total Cr can include species with very different mobility and toxicity, and its behavior may be influenced by localized inputs and oxidation-state changes. A future sequential-extraction or X-ray spectroscopy study would be needed to separate exchangeable, carbonate-bound, oxide-bound, organic/sulfide-bound and residual fractions.

Organic matter can further complicate the relationship between bulk sediment concentration and ecological exposure. Organic ligands may immobilize metals by complexation, but decomposition can consume oxygen and mobilize redox-sensitive phases. Ahmad et al. (2024) described autochthonous organic matter as a reversible sink for trace metals, underscoring that a sediment hotspot can alternate between retention and release. In mangrove channels, bioturbation by crabs, polychaetes and other benthic fauna can ventilate deeper layers, transport particles and modify porewater exchange. Thus, the

ecological significance of the Gazi and Vanga inventories depends not only on concentration but also on sediment reworking, organic-matter quality and the frequency of oxygenation events.

The negative salinity relationships should therefore be viewed as the field expression of several coupled processes. Lower salinity can indicate stronger terrestrial loading, greater delivery of fine particles and organic matter, and reduced dilution by offshore water. At the same time, salinity changes modify competition among ions, chloride complexation and particle flocculation. Jia et al. (2021) demonstrated that salinity-associated mixing and stratification can reorganize estuarine metal partitioning, while Zhao et al. (2024) showed that the direction and magnitude of mobility responses vary among metals and sediment types. The uniform negative coefficients in the present study reveal the net outcome of these processes, not a universal chemical law.

This interpretation has practical consequences for sediment-quality assessment. Comparing total concentrations with generic background values can identify enrichment but may not predict exposure where carbonate content and natural Fe-Mn abundance differ from the reference system. Regionally appropriate baselines, grain-size normalization and conservative-element normalization are therefore needed. They should be paired with a bioavailability metric such as porewater concentration, acid-volatile sulfide simultaneously extracted metals, diffusive gradients in thin films, or toxicity testing. Such additions would determine whether the same total concentration represents different ecological hazards at a sheltered mangrove station and a well-flushed coral-channel station.

Although the study covered one annual cycle, the process model is relevant to a wider climate context. The western Indian Ocean is exposed to changing rainfall intensity, marine heatwaves, sea-level rise and increasingly consequential coastal development. More intense runoff can increase catchment-derived particulate loads, while prolonged dry periods can concentrate contaminants in drainage networks before the first major rains. Storms and high-energy wave events may resuspend contaminated surface sediments, and sea-level rise can shift salinity intrusion and depositional zones landward. The present salinity-metal relationships therefore provide a baseline against which future hydroclimatic change can be evaluated.

The results also caution against treating annual mean concentrations as stable site attributes. A station can retain a large sediment inventory while displaying low dissolved concentrations during routine sampling. Conversely, a short disturbance can increase the labile fraction without measurably changing the annual mean total concentration. Dellapenna et al. (2020) showed how extreme hydrodynamic events can redistribute historically contaminated sediment, and Zafra-Mejia and Rondon-Quintana (2025) highlighted the availability of metals after runoff-driven resuspension. In Kenya, construction, dredging, vessel anchoring and shoreline modification may create analogous local disturbances even in the absence of an extreme regional event.

For management, the four sites should not receive identical monitoring intensity. Gazi is the strongest candidate for a permanent sentinel station because its multi-element sediment signal and low-salinity association indicate both accumulation and recurring catchment influence. Vanga should be monitored

as a transboundary estuarine zone where riverine inputs and tidal exchange intersect. Mkunguni requires surveillance linked to landing-site and vessel activity, whereas Shimoni provides a comparatively lower-concentration reference but should not be assumed pristine, especially where port development or dredging changes sediment dynamics. This risk-based allocation would be more efficient than evenly distributing a limited monitoring budget.

Source control remains essential. The multivariate pattern suggests mixed inputs, but concentration data alone cannot distinguish wastewater, agricultural runoff, antifouling paint, fuel combustion, boat repair, natural weathering and sediment inheritance. Studies in Environmental Pollution increasingly pair concentration mapping with isotopic tracers, molecular indicators and receptor modelling (Guo et al., 2023; Niu et al., 2023; Li et al., 2025). Applying Pb isotopes, rare-earth patterns, enrichment factors and land-use-linked source signatures would allow agencies to move from identifying hotspots to assigning responsibility and evaluating intervention effectiveness.

Finally, the study demonstrates why environmental monitoring should be explicitly connected to ecological and public-health surveillance. Sediment accumulation is an upstream warning, but risk is realized through bioavailability, benthic exposure, trophic transfer and seafood consumption. A coordinated program should therefore use common station identifiers and dates across hydrochemistry, sediment, invertebrate and fish sampling. This would make it possible to test lagged relationships and identify the conditions under which stored metals enter food webs. Such integration is necessary for evidence-based blue-economy development because it prevents pollution control, fisheries management and seafood safety from operating as separate policy domains.

A major strength was the matched station-month analysis across two environmental matrices and multiple hydrochemical variables. The design separated spatial, temporal and interaction effects and quantified standardized predictor strengths. The four-station gradient also captured contrasting estuarine and marine settings rather than treating the South Coast as a homogeneous unit.

Several limitations constrain inference. Total concentrations do not identify chemical species or bioavailable fractions. Sediment grain size, organic carbon, acid-volatile sulfide and Fe-Mn oxide fractions were not included in the regression set, so salinity may partly represent unmeasured depositional characteristics. Source apportionment was not performed, and observational regression cannot prove a causal salinity mechanism. Element-specific detection and quantification limits, recovery values and certified-reference-material results were unavailable for evaluation, limiting assessment of analytical uncertainty.

Finally, element-specific detection limits, recoveries and certified-reference-material results must be added from laboratory records before submission.

Future work should combine seasonal hydrodynamic measurements with sediment fractionation, porewater chemistry and passive samplers. Event-based sampling before and after heavy rainfall, dredging or storm disturbance would test whether total inventories and labile fractions respond

differently. Coupling these measurements with stable isotopes, benthic-invertebrate burdens and fish-tissue data would clarify the sequence from source to sediment storage to trophic exposure. Such studies would move regional monitoring from descriptive mapping toward predictive coastal pollution management.

5. Conclusions

Potentially toxic elements along Kenya's South Coast were controlled principally by local source-retention conditions rather than a uniform coast-wide seasonal cycle. Every measured element differed among stations in water and sediments, with Gazi consistently emerging as the strongest multi-element hotspot and Shimoni as the lower-concentration site. Sediments amplified and preserved this spatial signal.

Salinity and the associated conductivity-TDS gradient provided the main mechanistic explanation. Negative salinity relationships occurred for all sediment metals, and hydrochemical models explained up to 75% of variation. These results identify low-salinity, particle-retaining estuarine conditions as priority windows for surveillance. A defensible monitoring program should pair water and sediment sampling, include event-based observations, and incorporate labile fractions and biological sentinels before concluding that low dissolved concentrations represent low ecological risk.

Declarations

CRedit authorship contribution statement. Jane Moraa Nyamora: Conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing - original draft. James Njiru: Conceptualization, supervision, validation, literature synthesis, writing - review and editing. Albert Getabu: Conceptualization, supervision, field-method guidance, validation, writing - review and editing. Kobingi Nyakeya: Conceptualization, Methodology, validation, visualization, writing - review and editing.

Funding.

The study was funded by National Research Fund (NRF) of Kenya

Ethics and permits. Field research was conducted under the relevant Kenyan research authorization.

Data availability. The dataset analyzed is available from the corresponding author on reasonable request.

Declaration of competing interest. The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work.

References

1. Ahmad N, Singh SP, Sahu S, Bhattacharyya R, Maurya AS, Kumar N, Rout RK, Tripathy GR (2024) Isotopic evidence of autochthonous organic matter acting as a major sink of anthropogenic heavy metals in modern lacustrine sediments. *Environ Pollut* 349:123964. <https://doi.org/10.1016/j.envpol.2024.123964>
2. American Public Health Association (APHA) American Water Works Association (AWWA), & Water Environment Federation (WEF). (2017). *Standard Methods for the Examination of Water and Wastewater* (23rd ed.). American Public Health Association
3. Ali MM, Ali ML, Islam MS, Rahman MZ (2022) Distribution of heavy metals in water and sediment of an urban river in a developing country. *Stoch Environmental Res Risk Assessment* 36:3381–3398. <https://doi.org/10.1007/s00477-021-02100-0>
4. Atkinson CA, Jolley DF, Simpson SL (2007) Effect of overlying water pH, dissolved oxygen, salinity and sediment disturbances on metal release and sequestration from metal contaminated marine sediments. *Chemosphere* 69:1428–1437. <https://doi.org/10.1016/j.chemosphere.2007.04.068>
5. Ciszewski D, Grygar TM (2016) A review of flood-related storage and remobilization of heavy metal pollutants in river systems. *Water Air Soil Pollut* 227:239
6. Dellapenna TM, Hoelscher C, Hill L, Al Mukaimi ME, Knap A (2020) How tropical cyclone flooding caused erosion and dispersal of mercury-contaminated sediment in an urban estuary: The impact of Hurricane Harvey on Buffalo Bayou and the San Jacinto Estuary, Galveston Bay, USA. *Sci Total Environ* 748:141226
7. Du Laing G, Rinklebe J, Vandecasteele B, Meers E, Tack FMG (2009) Trace metal behaviour in estuarine and riverine floodplain soils and sediments: A review. *Sci Total Environ* 407:3972–3985. <https://doi.org/10.1016/j.scitotenv.2008.07.025>
8. El-Sharkawy M, Alotaibi MO, Li J, Du D, Mahmoud E (2025) Heavy metal pollution in coastal environments: Ecological implications and management strategies. *Sustainability* 17:701. <https://doi.org/10.3390/su17020701>
9. Guo Y, Wu C, Wang Z, Shi Y, Sun J (2023) Co-occurrence of toxic metals, bacterial communities and metal resistance genes in coastal sediments from Bohai Bay. *Environ Pollut* 338:122666. <https://doi.org/10.1016/j.envpol.2023.122666>
10. Jia Z, Li S, Liu Q, Jiang F, Hu J (2021) Distribution and partitioning of heavy metals in water and sediments of a typical estuary (Modaomen, South China): The effect of water density stratification associated with salinity. *Environ Pollut* 287:117277
11. Li Y, Zhang J, Song N, Wang Y, Yu J, He L, Yang R, Yang L, He D (2025) Assessment of health risk and identification of pollution sources of heavy metals in water in Chongqing's wastewater treatment plants based on ICP-MS. *Environ Pollut* 373:126193. <https://doi.org/10.1016/j.envpol.2025.126193>
12. McClanahan TR (1988) Seasonality in East Africa's coastal waters. *Marine Ecol Progress Ser* 44:191–199
13. Meschede MSC, Zagui GS, Celere BS, Machado GP, Gomes-Silva G, Santos DV, Sierra J, Nadal M, Domingo JL, Segura-Munoz SI (2024) Human exposure to elements through consumption of raw

- and cooked fish in an urban region of the central Brazilian Amazon biome: Health risks. *Environ Pollut* 347:123728. <https://doi.org/10.1016/j.envpol.2024.123728>
14. Miess S, Ipek Y, Dzialowski AR (2025) Heavy metal accumulation in deep sediment benthic invertebrates downstream from a historical mining district. *Environ Pollut* 386:127230. <https://doi.org/10.1016/j.envpol.2025.127230>
 15. Mwashote BM (2003) Levels of cadmium and lead in water, sediments and selected fish species in Mombasa, Kenya. *Western Indian Ocean J Mar Sci* 2:25–34
 16. Nario N, Gomez NA, Negrin VL, Marcovecchio JE, Garrido M, Domini CE (2025) An insight into sediment fractionation analysis: from sampling to visualisation of results. *Mar Pollut Bull* 218:118149. <https://doi.org/10.1016/j.marpolbul.2025.118149>
 17. Niu S, Xia Y, Yang C, Liu C (2023) Impacts of the steel industry on sediment pollution by heavy metals in urban water systems. *Environ Pollut* 335:122364. <https://doi.org/10.1016/j.envpol.2023.122364>
 18. Obura DO (2001) Can Differential Bleaching And Mortality Among Coral Species Offer Useful Indicators For Assessment And Management Of Reefs Under Stress? *Bull Mar Sci* 69:421–442
 19. Parikh A, Pansu J, Stow A, Warne MSJ, Chivas C, Greenfield P, Boyer F, Simpson SL, Smith RA, Gruythuysen J, Carlin G, Caulfield N, Viard F, Chariton AA (2024) Environmental DNA highlights the influence of salinity and agricultural run-off on coastal fish assemblages in the Great Barrier Reef region. *Environ Pollut* 349:123954. <https://doi.org/10.1016/j.envpol.2024.123954>
 20. Saidon NB, Szabo R, Budai P, Lehel J (2024) Trophic transfer and biomagnification potential of environmental contaminants (heavy metals) in aquatic ecosystems. *Environ Pollut* 340:122815. <https://doi.org/10.1016/j.envpol.2023.122815>
 21. Tao W, Jiang Z, Peng X, Yang Z, Cai W, Yu H, Ye J (2021) Impact of dredged material disposal on heavy metal concentrations and benthic communities in Huangmao Island marine dumping area near the Pearl River Estuary. *Appl Sci* 11:9412
 22. United States. EPA (2025) The EPA procedure defines surface sediment as material extending from the sediment–water interface to a maximum depth of 10 cm. Standard Operating Procedure (SOP) 1: Surface Sediment Sampling. SEMS Pub
 23. United States Environmental Protection Agency (USEPA) (2007) Method 6010C: Inductively Coupled Plasma–Atomic Emission Spectrometry. Revision 3. Washington, DC: U.S. Environmental Protection Agency
 24. Zafra-Mejia CA, Rondon-Quintana HA (2025) Analysis of the potential availability of resuspended heavy metals from urban road sediments: A post-runoff approach. *Environ Pollut* 387:127322. <https://doi.org/10.1016/j.envpol.2025.127322>
 25. Zhang H, Tang D, He J, Yang X, Feng Z, Fu Y, Ma S (2024) Assessment of heavy metal contamination in the surface sediments, seawater and organisms of the Pearl River Estuary, South China Sea. *Sci Total Environ* 950:175266

26. Zhao S, Wang Y, Chen L, Huang Q (2024) Effect of pH, temperature, and salinity levels on heavy metal mobility and bioavailability in aquatic sediments. Environmental Sci Pollution Res 31:31652–31668. <https://doi.org/10.1007/s11356-024-33370-6>

Figures

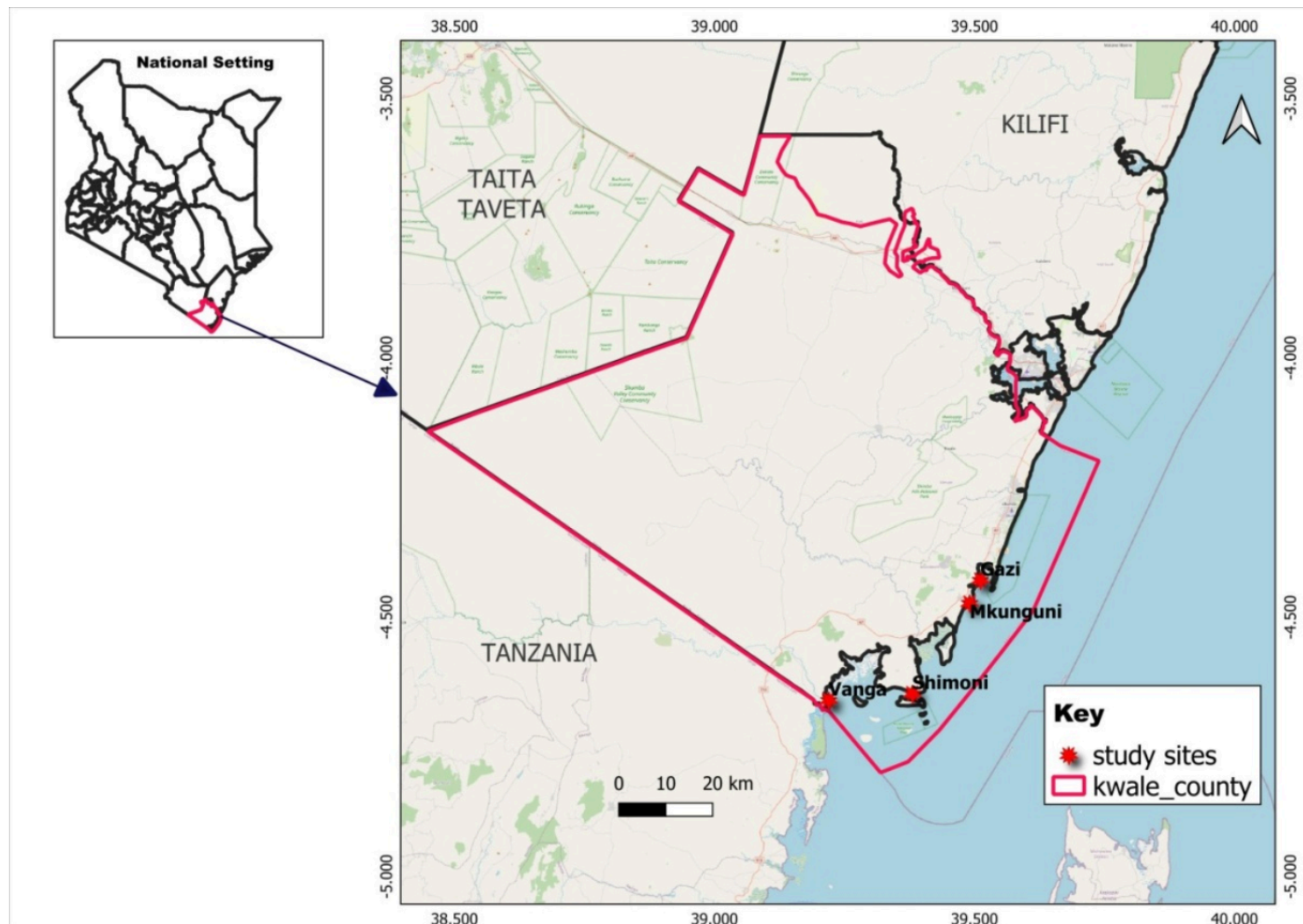


Figure 1

Location of Gazi, Mkunguni, Shimoni and Vanga sampling stations in Kwale County, Kenya.

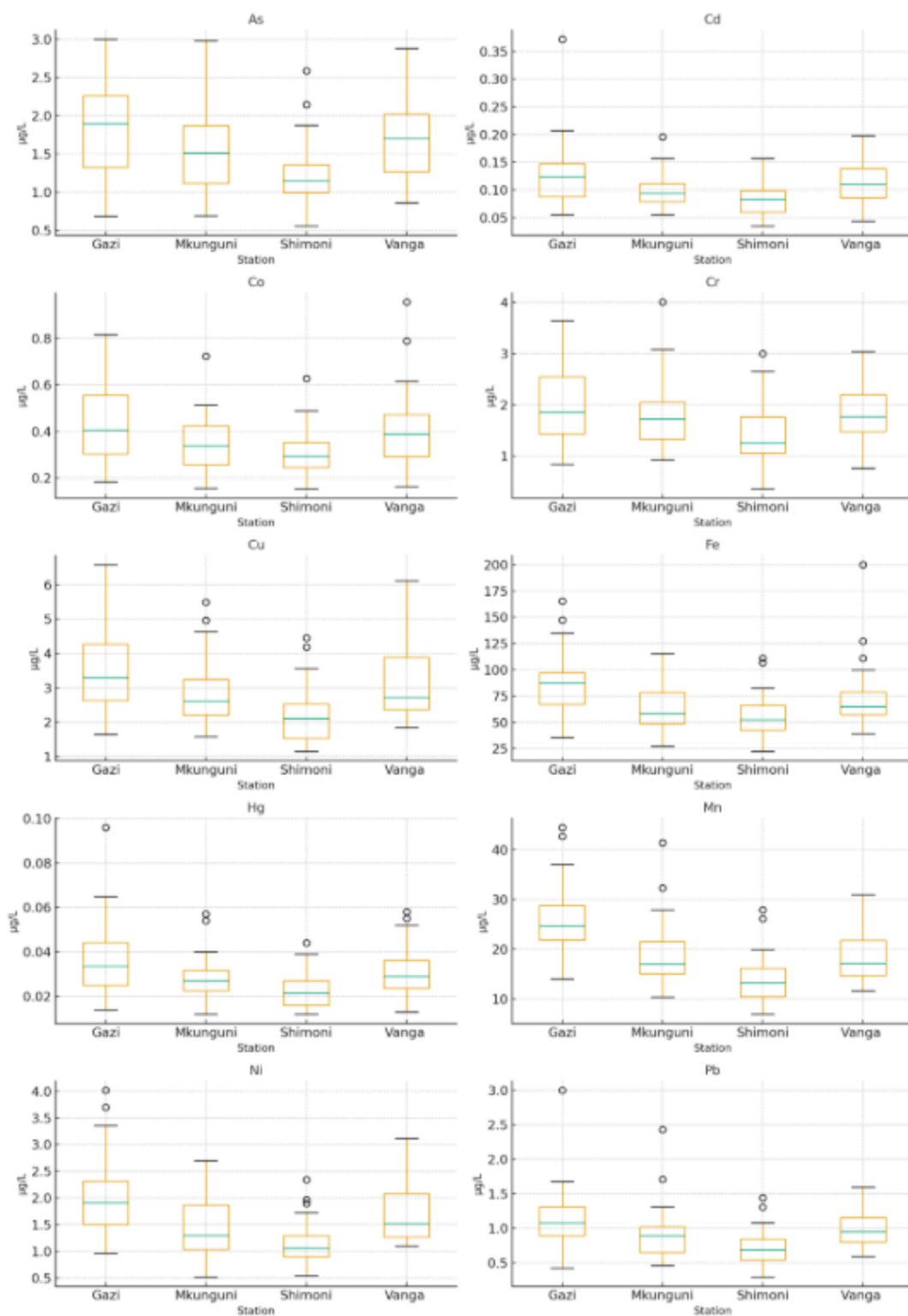


Figure 2

Spatial distributions of dissolved As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni and Pb across the four stations.

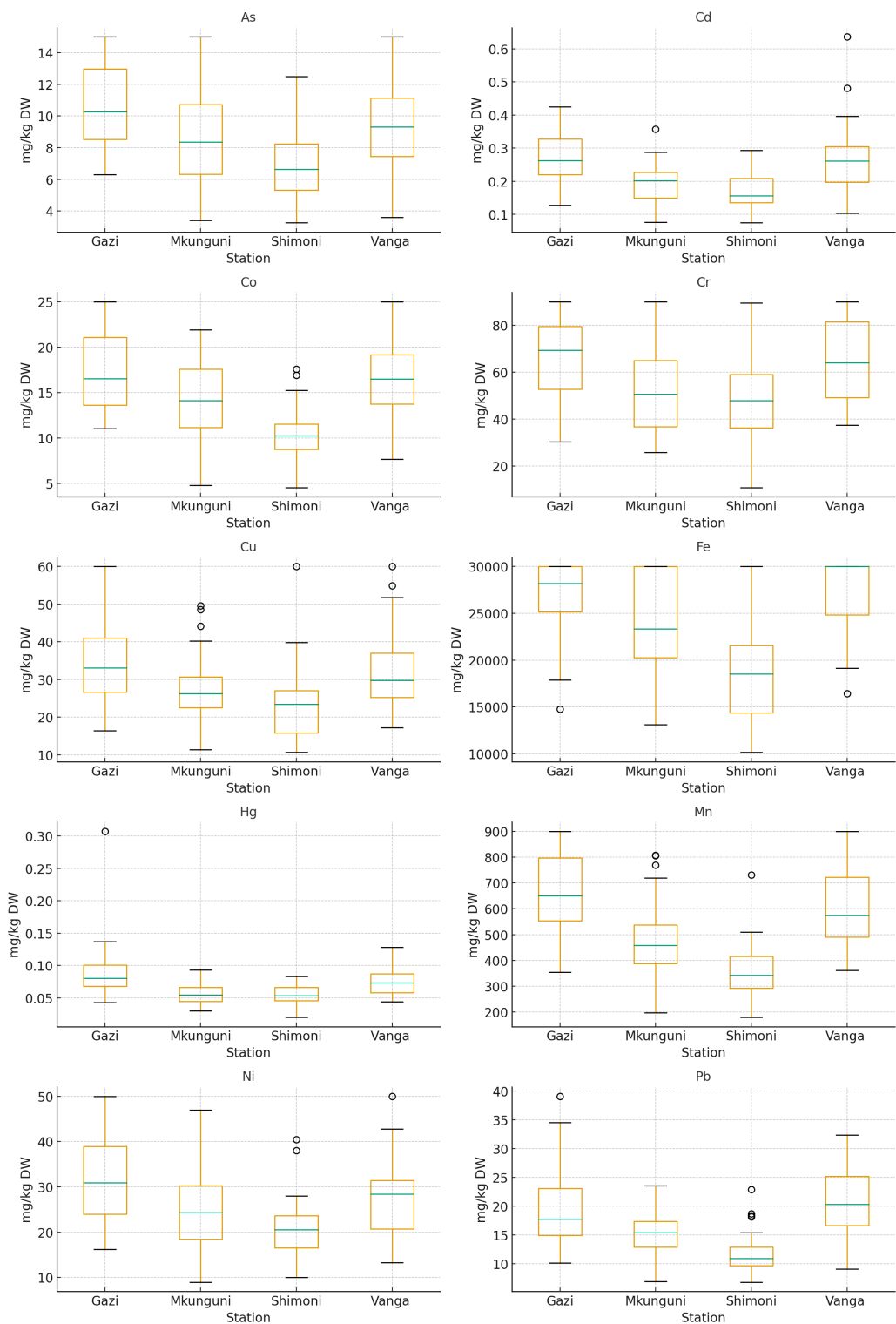


Figure 3

Spatial distributions of sediment associated As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni and Pb (mg/kg dry weight).

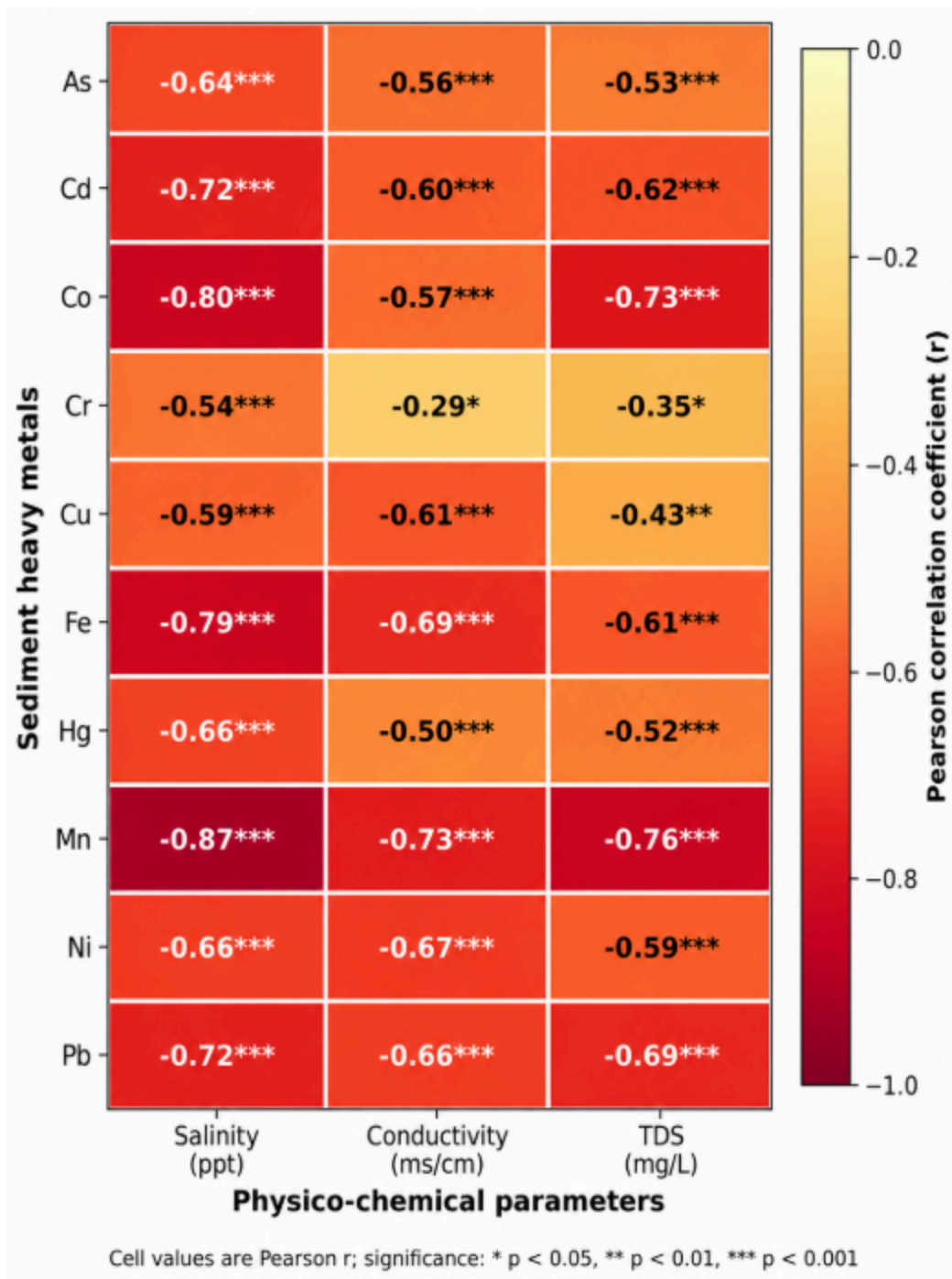


Figure 4

Correlation heatmap between hydrochemical variables and sediment metals. Negative salinity, conductivity and TDS associations dominate the matrix.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [floatimage1.png](#)