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Occurrence and Spatial Distribution of Chromium in Water Sources of Southeastern Turkana County, Kenya: An Exploratory Analysis

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Abstract

The phenomena of Cr occurrence in sources of water is critical major water-quality concern among the ASAL regime environments where communities rely upon dispersed groundwater and local water resources. This investigation evaluated total Cr in 39 water-source sites across eight administrative locations in southeastern Turkana County, Kenya. Of 78 duplicate data, S11B was not included given its absorbance surpassed the upper calibration standard, leaving 77 valid data. Total Cr was measured by AAS based on the empirical calibration equation: $A = 0.022602C - 0.011140$, where C is concentration in mg/L. Site averages varied from 0.8070 to 10.0385 mg/L (with a mean 3.8555 ± 2.5548 mg/L). Replicate agreement was variable (with median RPD of 26.56%). No statistically significant monotonic association was found with pH or surface altitude. Chromium was inversely related to distance from the chosen combined Ngamia 1&6 surface benchmark point ($\rho = -0.3263$, $p = 0.04262$), nonetheless, this exploratory association does not amount to source attribution. All 39 site averages surpassed the Kenyan and WHO total-chromium drinking-water standards (0.05 mg/L) and the US EPA maximum contaminant level (0.10 mg/L); 31 sites (79.5%) surpassed NEMA's 1.5 mg/L irrigation-water values. Nonetheless, speciation was not carried out in the present study; and current results denote total chromium, not Cr(III) or Cr(VI) separately. These results constitute a site-

specific benchmark and support confirmatory monitoring with strengthened analytical quality assurance and hydrogeochemical characterization.

Keywords: Arid and Semi-Arid Lands; Atomic absorption spectrometry; Geospatial distribution; Groundwater; Kenya, East Africa; Potable-water sources; Southeastern Turkana County; Total chromium

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Introduction

Water security in ASAL environments is deeply dependent on groundwater and a small range of complementary local sources, comprising shallow wells, boreholes, seasonal riverbed abstractions and springs. Under these hydrogeologic regimes, surface water resources are severely limited, highly ephemeral, or geographically inaccessible, underpinning domestic water resources, livestock production, and local socioeconomic development. Groundwater quality is thus as critical as its availability: this essential resource is highly susceptible to degradation from naturally occurring hydrogeochemical mechanisms and human activities (Marzouki et al., 2025; Ratandeep et al., 2024; Wang et al., 2023; Nyaberi et al., 2019).

Groundwater impairment in dryland environments is seldom a product of a discrete mechanism. Lithogenic factors and hydrochemical processes can influence ambient groundwater chemistry; however, multi-sectoral anthropogenic activities benchmark; however, may exert extra contaminant pressures or alter predominating mobilization pathways (Pandey et al., 2023; Tligui et al., 2025; Wang et al., 2023). Studies from semi-arid regions have documented water-quality degradations associated with salinity-related parameters, fluoride, nitrate and hazardous elements. These data underscore the necessity of assessing groundwater quality vis-à-vis both geogenic and anthropogenic determinants, acknowledging the site-specific heterogeneity of dominant processes and contaminant suites across distinct hydrogeologic regimes geologic regime(Marzouki et al., 2025; Pandey et al., 2023; Ratandeep et al., 2024).

Chromium necessitates specific attention in potable-water investigations given its occurrence and behavior in

groundwater rely upon hydrogeochemical dynamics and, in some regimes, industrial or mining-related contributions. Chromium manifests predominantly in natural waters as trivalent chromium, Cr(III), and hexavalent chromium, Cr(VI), which exhibit diversity fundamentally in transport and toxicological implication (Chrysochoou et al., 2016; Guo et al., 2024; Ning et al., 2025). Cr(VI) is of specific concern in drinking-water environments given it is typically more mobile and poses heightened toxicological concern than Cr(III). Hence, replicates of total Cr alone do not state the proportion present as Cr(VI), and interpretation of Cr occurrence must consider whether speciation has been considered (Chrysochoou et al., 2016; Guo et al., 2024). Pronounced groundwater Cr may stem from natural geologic sources, predominantly in aquifers related to ultramafic rocks or sediments originated from chromium-bearing materials (Botsou et al., 2021; Chrysochoou et al., 2016; Guo et al., 2024). Weathering can mobilize Cr(III) from mineral hosts; however, oxidation mechanisms associated with reactive manganese oxides may mediate the formation of Cr(VI). Under oxic and alkaline regimes, Cr(VI) can persist as a relatively mobile in groundwater (Botsou et al., 2021; Chrysochoou et al., 2016; Ning et al., 2025). The occurrence and persistence of dissolved Cr may also be contingent upon groundwater redox regimes, major-ion composition, residence time, recharge and the extent of water–rock interaction (Guo et al., 2024; Izbicki et al., 2015; Ning et al., 2025). These mechanisms constitute a geochemical framework for assessing Cr in groundwater. Nonetheless, their applicability to a specific study area must be evaluated vis-à-vis its geologic and hydrochemical attributes as opposed to being assumed from the wider literature.

The distribution of geogenic Cr is geospatially highly non-uniform and was not attributed solely to lithological factors. Research in California established that Cr(VI) occurrence was related not simply with chromium-bearing geologic materials, but also with groundwater regimes, comprising oxidation state, alkalinity and flow-path attributes (Izbicki et al., 2015). In Greece, enriched Cr(VI) was documented in alluvial and Neogene sediments originated from serpentine and amphibolite, nonetheless concentrations in waters related to some ophiolitic and metamorphic rocks were considerably low, underscoring the influence of groundwater contact regimes and hydrochemical attributes (Kaprara et al., 2015). Empirical findings from sedimentary aquifers further demonstrates that Cr may be mobilized internally from aquifer solids, with the propensity for mobilization contingent upon the oxidation of Cr(III) and the geochemical regimes predominating in the aquifer (Hu et al., 2022). In aggregate, these assessments demonstrate why Cr occurrence should be examined at the scale of individual groundwater systems and why geospatial differences should not automatically be interpreted as empirical findings of a specific contamination source.

These dynamics are particularly pertinent to southeastern Turkana County, where communities occupy a hot, water-scarce environment and rely upon dispersed water sources, comprising boreholes, shallow wells, streams and other locally existing resources. Turkana South lies within Kenya's ASAL areas, characterized by temperatures spanning 20 to 41°C and an annual precipitation of about 52–480 mm. Such climatic regimes severely limit the surface-water reliability resources and intensify the groundwater importance and other locally available sources (Nyaberi et al., 2019a, 2019b).

Previous groundwater assessments in Turkana South have highlighted systemic vulnerabilities related to rural water insecurity and reliance hand-dug wells, boreholes and stream-related abstractions (Nyaberi et al., 2019a, 2019b).

The hydrogeologic regime is highly non-uniform. Basement metamorphic and igneous rocks are predominant and characteristically impervious; however, groundwater Cr concentrations can be amplified locally by weathered, fractured and faulted zones. Recent river-channel sediments may also constitute regimes for shallow groundwater Cr enrichment and abstraction. Studies synthesizing remote sensing and vertical electrical sounding, and those integrating geologic, remote-sensing, GIS and borehole information, constitute complementary empirical findings on groundwater enrichment and the structural and lithological influence particularly pertinent to groundwater exploration in Turkana South (Nyaberi et al., 2019a, 2019b). These attributes are critical when elucidating water-quality variability given investigated sources may draw from diverse geologic materials, depths and groundwater flow environments. At the wider county scale, groundwater-quality investigations have also identified concerns associated with salinity, enriched total dissolved solids and electrical conductivity, and fluoride, although these results do not amount to the occurrence or distribution of Cr in the present investigation area (Makokha et al., 2024).

Southeastern Turkana is also part of the broader landscape that has undergone transformations related to petroleum exploration and associated infrastructure development latter to the discovery of oil in 2012. Exploration and development have encompassed the construction of well pads, roads, pipelines and water facilities; however, petroleum operations demand for water for drilling and associated mechanisms (Schubiger, 2026). Research from the Lokichar Basin has documented contamination concerns associated with produced water and enriched some metals and salts concentrations in target nearby boreholes. Such results are particularly pertinent to understanding propensity environmental pressures in the region, nonetheless, they are site-specific and was not taken as empirical findings that Cr contamination manifests across all stages of adjacent potable-water sources (Mbugua et al., 2022). Similarly, Turkana groundwater assessments have identified petroleum exploration and drilling among the activities necessitating environmental consideration; however, underscoring the need for site-specific empirical findings to amount to any related water-quality effects (Makokha et al., 2024).

Notwithstanding these developments and the broader literature on groundwater occurrence and quality in Turkana, empirical findings explicitly addressing Cr occurrence and its geospatial differences in potable-water sources persist as limited. Existing assessments have prioritized groundwater propensity and occurrence , salinity, fluoride and general physicochemical parameters; however, other work has considered the wider environmental and social dimensions of extractive development. However, these empirical findings strands do not amount to how Cr levels fluctuate among potable-water sources, administrative locations and hydrogeologic regimes in southeastern Turkana. This is a critical gap given Cr distribution may fluctuate with aquifer materials, groundwater chemistry, source attributes and local environmental regimes (Guo et al., 2024; Ning et al., 2025). A site-specific analysis is thus imperative to amount to an empirical

benchmark and describe the geospatial distribution of Cr in target water sources. The incorporation of spatial proximity to the Ngamia exploration area constitutes an extra geographical dimension for exploratory analysis; it is not intended to presume petroleum-related contamination or amount to a causal association between exploration activities and Cr occurrence .

Accordingly, this investigation examines the occurrence and Cr geospatial distribution in target potable-water sources in southeastern Turkana County, Kenya, and investigates its associations with target physicochemical and geographical parameters, comprising spatial proximity to the Ngamia exploration area. Specifically, the investigation aims to: (1) measure Cr levels in target potable-water sources in southeastern Turkana County; (2) characterize Cr differences across sample collection sites, administrative locations and water-source types; (3) scrutinize exploratory associations between Cr levels, pH and elevation; and (4) analyze geospatial variations in Cr levels vis-à-vis distance and direction from the combined Ngamia exploration benchmark area.

Methodology

Study Area and Geographical Setting

The investigation was carried out in southeastern Turkana County, Kenya, an arid to semi-arid environment characterized by high temperatures, low and variable rainfall, and dispersed human settlements. Turkana South has been documented to exhibit temperatures estimated at 20-41°C and about 52–480 mm annual precipitation. These climatic regimes underpin limited and seasonally variable surface-water availability and intensify reliance upon groundwater and other locally available water sources (Nyaberi et al., 2019b).

The hydrogeologic regime is highly non-uniform and encompasses basement metamorphic and igneous rocks, as well as sedimentary and volcanic formations. Groundwater occurrence in the basement terrain is strongly contingent upon geologic structures, predominantly faults, fractures and weathered zones. Integrated geologic, remote-sensing, GIS and borehole assessments in Turkana South have established geospatial variability in groundwater propensity related to geologic structures and lithological variability (Nyaberi et al., 2019a). Complementary remote-sensing and vertical electrical sounding assessments have identified lineaments, faulted and fractured zones, and weathered subsurface materials as propensity groundwater-bearing regimes (Nyaberi et al., 2019b).

Sample collection encompassed eight administrative locations in southeastern Turkana County: Lokichar, Katilia, Kaputir, Lokori, Lokwii, Morulem, Lokwamosing and Lotubae. The target water sources comprised the dispersed potable-water regimes within the investigation area and incorporated boreholes, hand pumps, shallow wells, swamps, water pans and springs.

The Ngamia exploration area was integrated as a geographical benchmark for exploratory spatial proximity and directional assessments. Ngamia 1 and Ngamia 6 were designated as a combined benchmark area given their surface coordinates are estimated at 56 m apart. Their incorporation constitutes a geospatial dimension for assessing whether measured Cr levels fluctuate with distance and direction from the exploration area. This does not claim causative effects of petroleum exploration activities for Cr in the investigated water.

Study Design and Water-Source Sample collection

The investigation utilized a cross-sectional exploratory design based on 39 distinct potable-water sample collection sites distributed across eight administrative locations in southeastern Turkana County. The sample collection sites comprised six water-source typologies recorded during fieldwork: boreholes, hand pumps, shallow wells, swamps, water pans and springs. The individual sample collection site served as the fundamental geospatial unit for geographical and site-level statistical assessments.

The analytical design integrated two replicates per sample collection site, identified based on the suffixes A and B. These replicates were utilized as duplicated data associated with the same sample collection site and were not designated as independent geographical locations. The original analytical dataset thus comprised 78 data from 39 sites.

Following analytical validation, one observation, S11B, was not included given its absorbance surpassed the upper limit of the established range of Cr calibration range. Its paired measurement, S11A, persisted as valid and was utilized. The final analytical dataset accordingly constituted of 77 valid data from the original 39 sites: 38 sites with valid A/B duplicates and one site (S11) comprised by a single valid measurement.

This differentiation between sample collection sites and laboratory data was observed across all stages of data processing. Observation-level assessments describe the full set of valid replicates, nonetheless site-level Aggregations constitute the framework for geospatial comparisons and mapping. The replicates were also utilized for descriptive analysis of within-site reproducibility.

Sample Designation, Handling and Laboratory Preparation

Every individual investigated water source was designated a distinct site identifier, with the 39 sites codified consecutively. Two replicates specimens or analytical data were identified based on the suffixes A and B, respectively. The A and B records were designated as duplicated replicates from the same site as opposed to being as independent geographical sample collection locality. Specimens were obtained unfiltered and acidified at collection with nitric acid (HNO_3) to pH < 2. Prior to aliquoting, every individual sample was vigorously mixed.

For sample processing 100 mL aliquot of the mixed, unfiltered sample was dispensed into a clean borosilicate beaker. About 3 mL of aqua regia solution was added. The mixture was subjected to mild thermal digestion on a hot plate within a fume hood at estimated at 85–95 °C and concentrated by evaporation, while avoiding boiling, to about 15–20 mL. Upon equilibration to room temperature, the beaker walls were washed down with about 30 mL of double-distilled water (DDW). The digest was filtered through clean Whatman No. 41 ashless filter paper (or equivalent), quantitatively dispensed to a 100 mL volumetric flask and made to volume with DDW.

Physicochemical Replicates

Field physicochemical information related to the investigated water sources spanned pH and, where recorded, temperature. These replicates were associated with the corresponding sample collection-site identifiers to enable their utilization in the descriptive and exploratory analysis of Cr differences. Utilized.

The pH data were utilized for exploratory analysis of the association between water acidity or alkalinity and Cr level. Surface elevation was also incorporated as a site-level geographical parameter in the latter analysis. Consolidated.

Chromium Determination and Analytical Calibration

The measured analyte was total Cr (Cr), expressed in mg/L. Chromium speciation was not performed; thus, the measured levels was not designated separately as Cr(III) or Cr(VI). Total Cr was measured by atomic absorption spectrometry (AAS) based on a Varian SpectrAA-200 instrument. Replicates were made at 357.9 nm based on a 0.2 nm slit width, a Cr hollow-cathode lamp current of 7 mA and an air–acetylene flame.

Quantification utilized a certified 1 g/L Cr stock standard to prepare 0, 5, 10 and 15 mg/L working standards. Their corresponding absorbances were −0.0039, 0.0890, 0.2189 and 0.3295, respectively. Absorbance (A) linear regression vis-à-vis concentration (C, mg/L) gave $A = 0.022602C - 0.011140$ ($R^2 = 0.9963$) as an empirical calibration association of the Beer–Lambert law over the working range estimated at 0.00769 absorbance units root mean square error (RMSE) and maximum absolute residual of estimated at 0.0129 absorbance units. consolidated.

Analytical Data Validation and Quality Considerations

The replicate observation S11B had a recorded absorbance of 0.3511, surpassing the highest calibration-standard absorbance of 0.3295. Thus it was not incorporated into the final Cr dataset. The paired observation, S11A, was within the valid analytical window and was retained so that even though S11B was excluded; the sample collection site itself was not removed, leaving the final Cr dataset with 77 valid data from 39 sample collection sites, with thirty-eight sites utilizing both replicate data; and one comprising of one valid observation..
consolidated

Data Processing and Descriptive Statistical Analysis

Data processing differentiated between the analytical-observation level and the sample collection-site level. The validated observation-level dataset comprised 77 Cr replicates, every individual associated with its original site identifier and replicate specification . Associated site information incorporated locality, water-source typology, geographical coordinates and elevation, together with the existing physicochemical determinations. Observation-level Aggregations were employed to represent the full set of valid Cr replicates.

For the 38 sites with valid duplicate data, the site-level Cr value was computed as the average of the two utilized replicates. For S11, the single valid measurement was utilized as the site-level value.

Descriptive statistics incorporated computation of the number of data or sites, minimum, maximum, mean, median and standard deviation. Chromium concentrations were aggregated at observation and site levels, with extra descriptive Aggregations by locality and water-source typology. Site-level values were employed for geographical comparisons and mapping; nonetheless, observation-level values were utilized for profiling the consolidated validated analytical dataset and assessing replicate differences. The differentiation between these two levels of analysis was observed across all stages of the study.

Water-Source and Physicochemical Comparisons

Descriptive comparisons were made among the six recorded water-source typologies (boreholes, hand pumps, shallow wells, swamps, water pans and springs) and across the eight administrative locations. These aggregations were computed from the final site-level dataset of 39 sites, based on one site average per sample collection location.

Site-level Cr values were applied for computing locality and source-typology aggregations. Descriptive statistics (means, standard deviations, medians and ranges) were computed as appropriate. Nonetheless, source-typologies were predominated by boreholes and four typologies comprised only one site and hand pumps comprised four sites.

Spearman's rank correlation coefficient (ρ) was applied for exploratory associations. The pH sensitivity result was based on the 77 valid observation-level Cr replicates ($\rho = -0.0592$, $p = 0.7202$); and surface altitude was evaluated at the 39-site level ($\rho = 0.1783$, $p = 0.2774$) as exploratory tests and not necessarily as causal associations between physicochemical regimes, topographic position and the water Cr occurrence in the region.

2.9 Spatial and Spatial proximity Analysis

Geographical coordinates for the 39 sample collection sites were used to prepare maps illustrating the distribution of sample collection locality and their corresponding site-level Cr levels, representing the geospatial distribution of investigated sites and their measured values.

The exploratory spatial proximity analysis utilized a combined Ngamia 1–Ngamia 6 benchmark area. The two wells were comprised surface coordinates estimated at just 56 m apart and were thus conceptualized as a single geographic benchmark for the scale of the present analysis, as opposed to being treated as two independent reference localities. The combined benchmark point was located at approximately 2.20753° N and 35.76058° E. This was to avoid treating close surface coordinates as distinct geospatial points in the spatial proximity analysis. this, however does not presume that the two wells have identical subterranean regimes and the combined point denotes a verified source of Cr contaminant.

The distance from every individual sample collection site to the combined benchmark point was computed based on the site and benchmark coordinates. Site-level Cr values were then assessed vis-à-vis distance. For descriptive comparison, the 39 sites were ranked by distance and partitioned into spatial proximity quartiles. Chromium levels were aggregated across these proximity groups, and the nearest and farthest quartiles were compared as an exploratory analysis of possible geospatial variability.

The bearing from the combined benchmark point to every individual sample collection site was also computed and assigned to the eight directional sectors: north, northeast, east, southeast, south, southwest, west and northwest. These directional zones were used to describe the geographical distribution of sample collection sites and to investigate whether Cr replicates displayed directional variability around the benchmark area. Directional assessments were interpreted in the context of the number of sites included in every individual sector.

Rank-based investigations were utilized to scrutinize the association between site-level Cr level and distance from the combined benchmark point, and

to analyze distance-related variations within directional zones where the number of data allowed calculation. In cases where multiple directional tests were factored in, the Benjamini–Hochberg procedure was applied to adjust *p*-values for multiple comparisons. These assessments were exploratory rather than claim of causal association with petroleum exploration or production activities at the reference region. Geological regimes, groundwater flow, source attributes and other anthropogenic determinants may also underpin geospatial variability.

Statistical Significance and Analytical Software

Inferential assessments were evaluated based on two-sided tests, at $p<0.05$ significance thresholds. Spearman's rank correlation was utilized for the specified associations linked to chromium, pH, surface altitude surface altitude and distance. in instances where multiple directional-sector tests were performed , again *p*-values were adjusted based on the Benjamini–Hochberg procedure to mitigate the false-discovery rate. Descriptive comparisons were evaluated with cognizant of sample size, replicate structure and the exploratory nature of the study.

All geographical assessments and locality/source-typology aggregations were based on the 39 sample collection sites as the geospatial units. Observation-level aggregations utilized the 77 valid Cr replicates; however, replicate agreement was evaluated separately.

Results

Sample collection Coverage and Validated Analytical Dataset

The investigation covered 39 distinct potable-water sample collection sites distributed across eight administrative locations in southeastern Turkana County: Lokichar, Katilia, Kaputir, Lokori, Lokwii, Morulem, Lokwamosing and Lotubae. The investigated sources comprised six typologies: boreholes, hand pumps, shallow wells, swamps, water pans and springs.

The original analytical dataset constituted of 78 data, with two replicate specimens designated A and B for every individual sample collection site. Following empirical data curation, one observation, S11B, was not included given its absorbance surpassed the upper calibration limit. The final dataset accordingly comprised 77 valid Cr data from the original 39 sites. Thirty-eight sites utilized two valid replicates; however, site S11 was comprised by the single valid measurement S11A. The exclusion compromises the spatial representation of the sampling network .

Chromium Calibration and Analytical Data Validation

The four calibration standards (0, 5, 10 and 15 mg/L) demonstrated a strong linear association between Cr concentration and the absorbance. The calibration framework and resultant regression analysis are detailed in Table 1 and Figure 1.

Table 1. Chromium calibration standards and empirical regression

Standard concentration (mg/L)	Absorbance
0	−0.0039
5	0.0890
10	0.2189
15	0.3295

Note. Linear regression: A = 0.022602C − 0.011140; R^2 = 0.9963; RMSE ≈ 0.00769 absorbance units; maximum absolute residual ≈ 0.0129. C is total Cr level (mg/L).

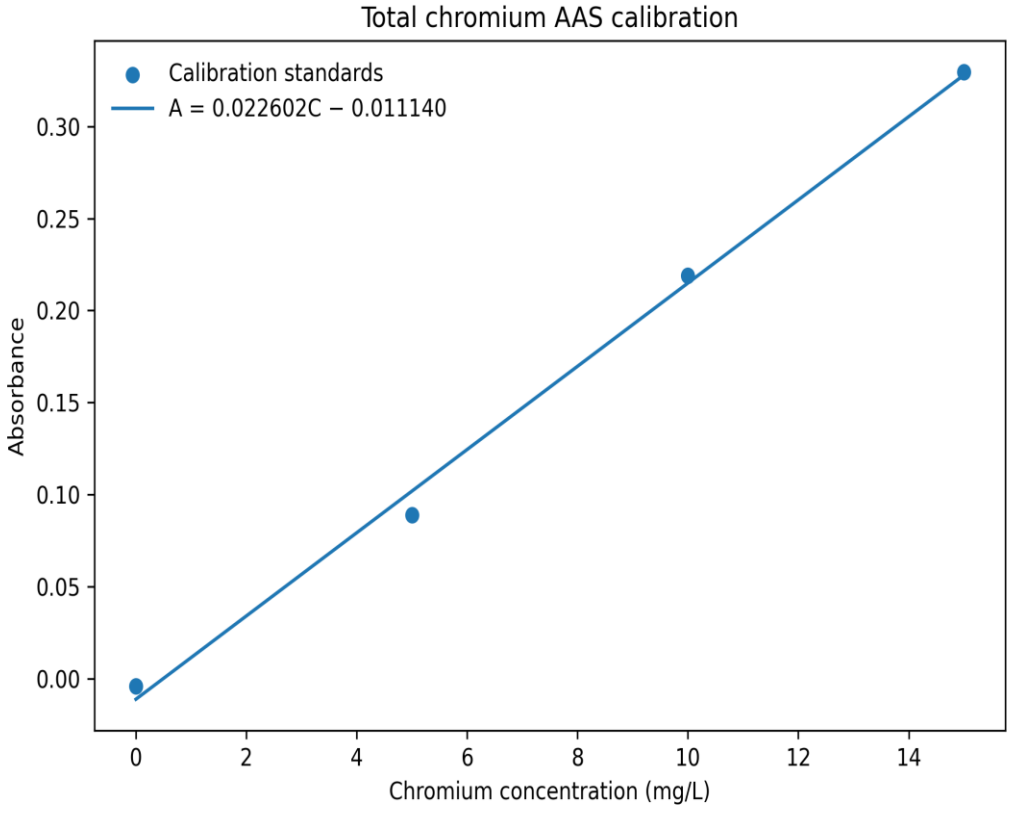


Figure 1. Empirical AAS calibration curve for total Cr based on four standards (0–15 mg/L).

Validation of sample absorbances vis-à-vis the established linear range revealed that one measurement exceeded the upper quantification limit. The observed absorbance for S11B was 0.3511, surpassing the maximum standard absorbance of 0.3295. This observation was not included given its concentration exceeded the upper limit of quantification (ULOQ). The paired replicate, S11A, persisted within the calibration range and was utilized. The exclusion was thus an analytical-range decision as opposed to being a statistical outlier decision.

The resulting 77 data served as the validated Cr dataset for the descriptive, correlation and geospatial assessments ..

Observation-Level and Site-Level Chromium Levels

The distributions in observation-level and site-level chromium levels are aggregated in Table 2.

Table 2. Descriptive statistics for total chromium

Statistic	Valid data (n = 77)	Site averages (n = 39)
Mean (mg/L)	3.8451	3.8555
Standard deviation (mg/L)	2.8274	2.5548
Median (mg/L)	3.1918	3.2891
Minimum (mg/L)	0.5814	0.8070

Maximum (mg/L)	10.4124	10.0385

Note. Site averages are based on two valid replicates at 38 sites and one valid measurement at S11.

The observation-level and site-level averages were similar. Site-level values reflect the aggregated arithmetic mean of two valid replicates at 38 sites and the single valid result at S11.

Reproducibility of Replicate Chromium Determination

Replicate agreement was evaluated on the 38 sites with two valid Cr duplicate values and the results summarized in Table 3.

Table 3. Agreement between replicate total-chromium replicates

Metric	Result
Sites with two valid replicates	38
Sites with one valid replicate	1 (S11)
Median absolute difference	0.6393 mg/L
Maximum absolute difference	8.1851 mg/L
Median relative percentage difference	26.56%
Maximum relative percentage difference	154.50%

These results showed considerable variability in agreement between the replicate values. While the median variability fell below the maximum observed discrepancies, the large upper values demonstrate that some replicate duplicates differed fundamentally. Replicate differences were thus employed as a critical analytical consideration when elucidating site-level averages and geospatial variations.

Chromium Levels across Water-Source Types

The 39 final sites averages were aggregated across the six water-source typologies (Table 4).

Table 4. Site-level total Cr by water-source typology

Water-source typology	Sites (n)	Mean (mg/L)	SD (mg/L)	Median (mg/L)	Range (mg/L)
Shallow Well	1	7.2113	—	7.2113	7.2113–7.2113
Borehole	31	4.0526	2.6688	3.4683	0.8070–10.0385
Water Pan	1	3.0701	—	3.0701	3.0701–3.0701
Hand Pump	4	2.8660	1.4294	2.3036	1.8866–4.9704
Swamp	1	1.6808	—	1.6808	1.6808–1.6808
Spring	1	1.3092	—	1.3092	1.3092–1.3092

These source-typology averages were originated directly from the final 39-site dataset. Borehole sources comprised 31 sites (mean 4.0526 mg/L), hand pumps four sites (mean 2.8660 mg/L), and shallow wells, springs, swamps and water pans one site every individual (with means of 7.2113, 1.3092, 1.6808 and 3.0701 mg/L, respectively).

Associations between Chromium Concentration, pH and Elevation

Spearman rank correlations were applied to scrutinize the associations between chromium concentration, pH and elevation. The pH sensitivity result was based on 77 valid data, nonetheless the surface altitude surface altitude result was based on 39 sites (Table 5).

Table 5. Spearman associations of Cr with pH and elevation

Variable	Analysis unit (n)	Spearman's ρ	p-value	Interpretation
pH	77 data	−0.0592	0.7202	Not statistically significant
Elevation	39 sites	0.1783	0.2774	Not statistically significant

Neither association was statistically significant at the 0.05 level.

Site-Level Distribution and Spatial Variation

Site-level average total Cr varied across the 39 sample collection locality, spanning 0.8070 to 10.0385 mg/L. The locality aggregations are detailed in Table 6, the five highest sites averages in Table 7 and Figure 2, and the observed-site point distribution in Figure 3.

Table 6. Site-level total Cr by locality

Locality	Sites (n)	Mean (mg/L)	SD (mg/L)	Median (mg/L)	Range (mg/L)
Katilia	8	5.4924	3.3859	6.1118	1.0902–10.0385
Kaputir	2	4.6894	0.8603	4.6894	4.0811–5.2978
Lokichar	11	4.2962	2.3481	3.5015	1.8866–9.2377
Lokori	8	3.9287	2.2509	3.3134	1.1676–7.3573
Lokwamosing	3	2.9875	1.1946	3.2581	1.6808–4.0235
Morulem	3	1.4109	0.8971	0.9840	0.8070–2.4418
Lokwii	2	1.3424	0.6695	1.3424	0.8689–1.8158
Lotubae	2	1.2395	0.0798	1.2395	1.1831–1.2959

Table 7. Five sites with the highest average total chromium

Rank	Site	Locality	Mean total Cr (mg/L)	Valid replicates (n)
1	S18	Katilia	10.0385	2
2	S1	Lokichar	9.2377	2
3	S20	Katilia	8.1714	2
4	S5	Katilia	8.0365	2
5	S21	Lokori	7.3573	2

Note. Rankings utilization final site averages; S11 is comprised by one valid measurement nonetheless, is not among the five highest sites.

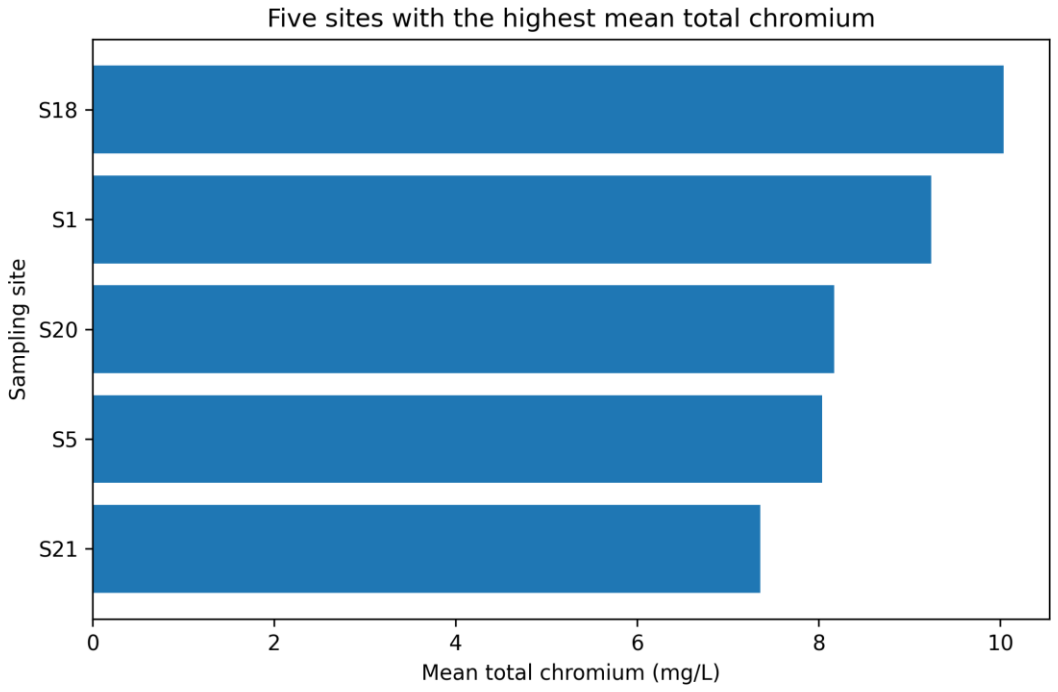


Figure 2. Five sample collection sites with the highest final site-level average total Cr levels (mg/L).

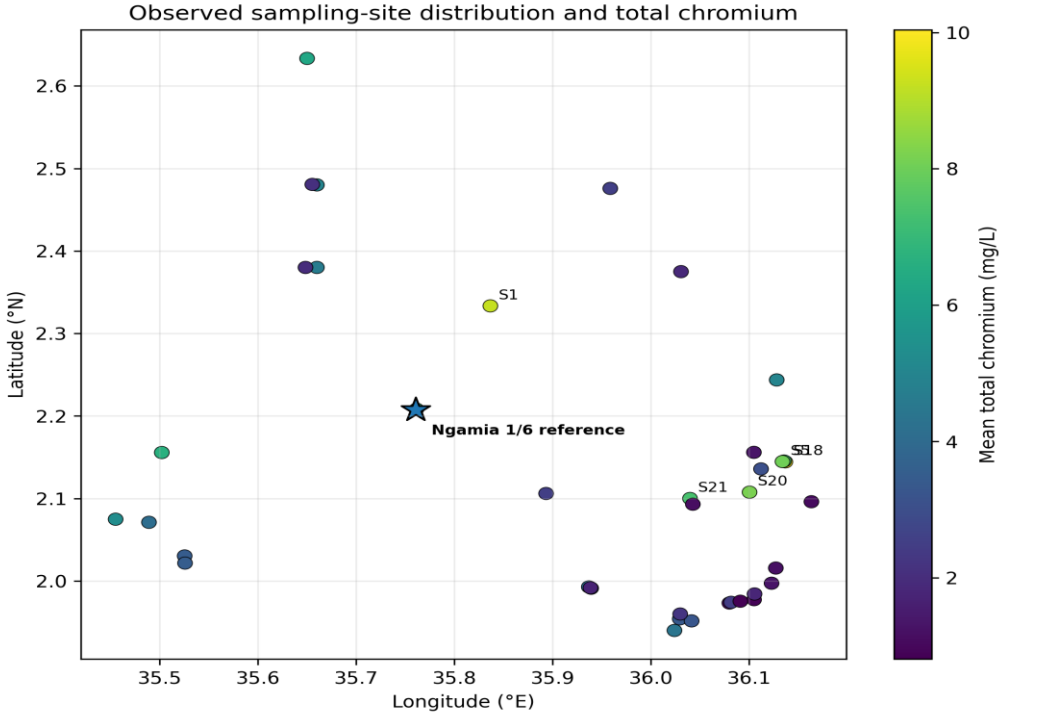


Figure 3. Observed sample collection-site coordinates and final site-level average total Cr levels (mg/L) vis-à-vis the combined Ngamia 1&6 surface benchmark point (star). (*NB: The five highest site averages are labelled. Only measured locality is plotted; no interpolation or contamination-risk surface is demonstrated.*)

The geographical distribution of sample collection sites spanned all eight investigation administrative locations. The site-level map represents the measured values at the investigated points..

Chromium Distribution in Relation to the Combined Ngamia Benchmark Area

The association between site-level total Cr and distance from the combined Ngamia 1–Ngamia 6 benchmark point was scrutinized based on 39 sites. The combined surface benchmark, representing the two well coordinates separated by 56.06 m, was at 2.20753° N, 35.760576° E .

For a complementary comparison, sites were ranked by distance and partitioned into quartiles. The pattern was not a simple monotonic decline across all four distance groups and the distance-quartile aggregations are detailed in Table 8 and the distance association in Figure 4.

Table 8. Site-level total Cr by distance quartile from the combined Ngamia benchmark point

Distance quartile	Sites (n)	Mean Cr (mg/L)	Median Cr (mg/L)	SD (mg/L)	Mean distance (km)
Q1_nearest	10	4.6124	4.3421	2.4537	23.4889
Q2	10	3.2676	3.0026	1.9358	34.7587
Q3	9	4.9723	4.3863	2.2801	41.1568
Q4_farthest	10	2.6814	1.2395	3.0609	45.5189

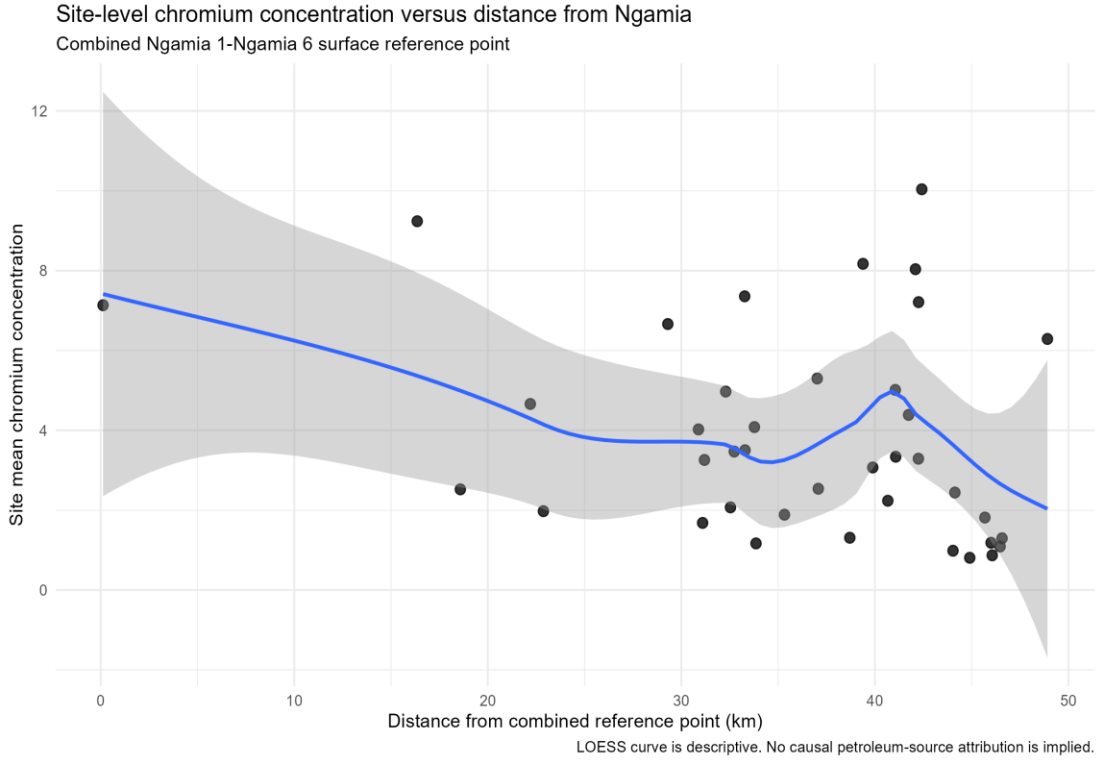


Figure 4. Site-level average total Cr level (mg/L) versus distance from the combined Ngamia 1&6 surface benchmark point. The fitted LOESS curve is descriptive; the association is exploratory and does not presume nor claim petroleum-source attribution.

A Wilcoxon rank-sum comparison between the nearest and farthest quartiles returned a test statistic of 80 and a p-value of 0.02575 (Table 9).

Table 9. Overall geospatial association between total Cr and distance from the Ngamia benchmark point

Analysis	Result
Sites (n)	39
Spearman's ρ	−0.3263
Two-sided p-value	0.04262
Nearest-quartile sites	10
Farthest-quartile sites	10
Wilcoxon rank-sum statistic	80
Wilcoxon rank-sum p-value	0.02575

This results demonstrates a difference in the distributions of site-level total Cr values between these two distance groups.

Combined Ngamia Benchmark Point

Sample collection sites were divided into eight directional sectors in relation to the combined Ngamia benchmark point. Sector Aggregations are demonstrate in Table 10 and Figure 5.

Table 10. Directional distribution of site-level total chromium

Direction	Sites (n)	Mean (mg/L)	Median (mg/L)	SD (mg/L)
N	3	4.4431	4.9704	2.1582
NE	4	5.1988	4.8354	3.5643
E	10	5.2464	6.1118	3.3636
SE	15	2.2753	2.2361	1.1724
S	0	—	—	—
SW	4	4.0871	3.7913	0.8547
W	1	6.6627	6.6627	—
NW	2	3.3178	3.3178	1.8990

Note. Sector sample sizes are uneven; for instance, . the west zone had one site and south, none.

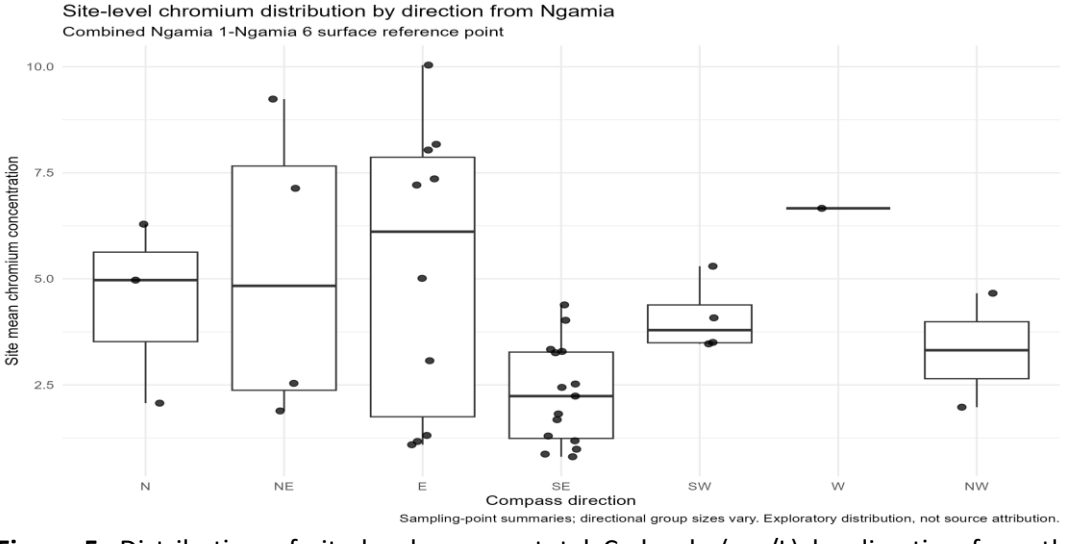


Figure 5. Distribution of site-level average total Cr levels (mg/L) by direction from the combined Ngamia 1&6 surface benchmark point.

Sector-specific rank correlations between Cr levels and distance were also scrutinized where the site sample size was sufficient to support the calculation. The southeast sector demonstrated a negative association (ρ=-0.621;, p=0.0134); this persisted as statistically significant following Benjamini–Hochberg adjustment (*p*-value i.e. ($p_{adjusted}$ = 0.0335))). The northeast and east sectors demonstrated marginal, statistically negligible correlations. The north sector comprised only three sites; however, the west and northwest sectors comprised one and two sites, respectively, confounding meaningful inferential analysis. The southwest sector comprised four sites and yielded a perfect rank correlation within the recorded output even though the result is derived very few data, and may not provide sufficient robust directional gradient.

Comparison with drinking-water and other water-use benchmarks

The aggregate site-level average was 3.8555 mg/L (median 3.2891 mg/L; range 0.8070–10.0385 mg/L). All 39 site averages surpassed the Kenyan drinking-water standard of 0.05 mg/L (KS 05-459, WASREB), the WHO thresholds of 0.05 mg/L for total Cr, the EU parametric value of 0.05 mg/L, and the US EPA total-chromium upper contaminant limit of 0.10 mg/L.

Relative to the Kenyan NEMA 2024 value of 1.5 mg/L for irrigation water, as a non-drinking water secondary water-use benchmark, 31 of 39 sites (79.5%) surpassed then 1.5 mg/L mark. At locality level, all eight localities averages surpassed 0.10 mg/L and five of eight surpassed 1.5 mg/L. At source-typology level, all six typology averages surpassed 0.10 mg/L; however, five of six surpassed 1.5 mg/L. The benchmark comparisons are aggregated in Table 6.

Table 6. Comparison of site, locality and source-typology averages with target water-quality benchmarks

Benchmark and scope	Value (mg/L)	Overall average / value	Sites surpassing	Locality averages surpassing	Source-typology averages surpassing
Kenya drinking-water standard (KS 05-459; reproduced by WASREB) — Drinking water	0.050	77.1×	39/39 (100.0%)	8/8	6/6
WHO guideline for total Cr — Drinking water	0.050	77.1×	39/39 (100.0%)	8/8	6/6
EU Directive 2020/2184 — current value through 11 Jan 2036 — Drinking water	0.050	77.1×	39/39 (100.0%)	8/8	6/6
EU Directive 2020/2184 — future value from 12 Jan 2036 — Drinking water; future requirement	0.025	154.2×	39/39 (100.0%)	8/8	6/6
US EPA maximum contaminant level for total Cr — Drinking water	0.100	38.6×	39/39 (100.0%)	8/8	6/6

Kenya NEMA 2024 Ninth Schedule — irrigation water — Irrigation water; not a drinking-water standard	1.500	2.6×	31/39 (79.5%)	5/8	5/6

Note. "Exceeding" is computed based on the 39 final site averages, eight locality averages and six source-typology averages. The NEMA 1.5 mg/L value is for irrigation water (Ninth Schedule), not drinking water. The EU value is 0.05 mg/L until 12 January 2036; 0.025 mg/L is the future requirement from that date.

These are comparisons of observed total Cr with published values; not Cr species-specific values, exposure doses, health outcome or source attribution.

Discussion

Chromium occurrence and geospatial heterogeneity in southeastern Turkana

The results demonstrate that Cr was observable across the investigated potable-water sources, with significant variability among sample collection sites (Table 2). This finding constitutes an initial indication that Cr occurrence in the investigation area is not geospatially uniform. The variability is environmentally particularly pertinent given water sources from the same broad dryland region may exhibit diversity in their geologic regime, aquifer materials, groundwater residence time and local hydrochemical regimes. However, the observed variability should be interpreted as geospatial differences in the measured Cr parameter as opposed to being empirical findings of a specific contamination mechanism.

This interpretation aligns with the broader groundwater literature, which demonstrates that Cr occurrence can be strongly contingent upon geologic and hydrogeochemical regimes. Guo et al. (2024), in their global review of geogenic Cr in groundwater, recognize aquifer mineralogy, redox regimes, dissolved oxygen (DO), pH and interactions between chromium-bearing solids and groundwater as critical factors on Cr mobilization and persistence. Their review further shows that enriched groundwater Cr is not imitated to a single aquifer type, even if many recognized high-chromium systems are related to ultramafic rocks or sediments originated from such rocks. The applicability of this literature to Turkana is thus conceptual: it defines the range of possible geologic and geochemical factors that should be examined, nonetheless, does not reveal that the same mineralogical regimes or Cr mobilization pathways manifest at the present sample collection sites.

The hydrogeologic regime constitutes a plausible framework for assessing such geospatial variability. Nyaberi et al. (2019a) established that groundwater propensity in Turkana South diverges with geologic structures, lithological contrasts, faulting, fracturing and weathering. Their integrated geologic, remote-sensing and borehole analysis demonstrated that groundwater occurrence is geospatially highly non-uniform and structurally influenced. Nyaberi et al. (2019b) similarly identified associations between lineament variations, faulting, weathered formations and groundwater propensity based on remote sensing and vertical electrical sounding. These assessments constitute critical local hydrogeologic dimensions for elucidating the present geospatial data. Nevertheless, groundwater-propensity mapping is not equivalent to groundwater-quality analysis. The structural features established by Nyaberi et al. may influence groundwater occurrence and

flow, nonetheless, their association with Cr levels in the investigated sources persist ass to be established.

The geospatial variability observed in this investigation thus underscores the necessity of site-specific groundwater-quality analysis in southeastern Turkana. Regional or locality-wide generalizations about Cr occurrence would be inappropriate where aquifer regimes and water-source attributes may fluctuate over relatively short distances. The present results constitute a benchmark for identifying locality that necessitate confirmatory sample collection, as opposed to being a definitive delineation of chromium-affected aquifers.

Comparison with drinking-water and other water-use benchmarks

The benchmark comparison positions the observed site-level total Cr levels significantly higher than several drinking-water benchmark values. All 39 site averages surpassed the Kenyan drinking-water standard of 0.05 mg/L and the WHO guidelines of 0.05 mg/L for total chromium. The same 39 sites surpassed the contemporary EU value of 0.05 mg/L, , and the US EPA maximum contaminant level of 0.10 mg/L. The EU Directive stipulates a revised threshold of 0.025 mg/L to be achieved by 12 January 2036 (European Parliament and Council of the European Union, 2020; U.S. Environmental Protection Agency, last updated on March 4, 2026; Water Services Regulatory Board, 2023.; World Health Organization, 2022).

The NEMA value of 1.5 mg/L necessitates a different reading. It is detailed in the Ninth Schedule of Kenya's 2024 Water Quality Regulations as a allowable level for irrigation water, and not as the benchmark for domestic drinking-water. Thirty-one sites surpassed this reference value. It is thus incorporated as a secondary water-use comparison (National Environment Management Authority, 2024). The domestic-water specifications within the retrieved regulations do not prescribe chromium values; the Kenyan drinking-water comparison in this investigation uses the KS 05-459 value reproduced by WASREB.

The consistent exceedance across all administrative locations and source-typology averages demonstrates that the observed total Cr levels were not confined to a single locality or source typology within this dataset. However, source-typology sample sizes were uneven, and four typologies were comprised by one site every individual. These aggregations should accordingly be interpreted as descriptive. Furthermore, the comparison is not a consolidated analysis of drinking-water safety: it does not specify Cr speciation, and exposure analysis. The results necessitate confirmatory determination and careful follow-up, as opposed to being treated as an unqualified condemnation all sources as unsafe.

Hydrogeologic and geochemical factors controlling Cr variability

Geogenic mobilization is an critical factor to consider in groundwater Cr assessments. Chromium occurs naturally in aquifers and can get into groundwater via mineral weathering, dissolution and oxidation–reduction processes. Guo et al. (2024) describe the significance of chromium-bearing aquifer materials and manganese oxide-mediated oxidation mechanisms in certain bedrock and sedimentary aquifers. They demonstrate that groundwater redox regimes, pH and residence time can influence Cr transport and distribution. These mechanisms illustrate why Cr levels was not interpreted independently of the

geologic and hydrochemical attributes of the groundwater system.

The geologic complexity reported in Turkana South makes this framework particularly pertinent to the present work. The area encompasses basement formations, volcanic rocks and younger sedimentary deposits; however, groundwater occurrence is contingent upon weathered zones, fractures and faults (Nyaberi et al., 2019a, 2019b). Variability in the composition and weathering attributes of these formations could potentially generate geospatial variability in naturally occurring trace elements. However, the present investigation did not measure Cr levels in aquifer solids, mineralogical composition, groundwater redox potential, DO, major-ion chemistry or Cr speciation. Hence, it does not claim to elucidate whether the observed Cr variations emanate from geogenic mobilization, variability in groundwater chemistry, anthropogenic contributions or a combination of these determinants.

The differentiation between Cr oxidation states are especially critical. Cr(III) and Cr(VI) exhibit diversity fundamentally in their aqueous behavior, transport and toxicological implication . Guo et al. (2024) describe regimes under which Cr(III) may be oxidized to Cr(VI), comprising reactions associated with manganese oxides in specific aquifer environments. Izbicki et al. (2015), assessing public-supply wells in California, also established that Cr(VI) occurrence was related to interacting geologic, hydrological and geochemical regimes, comprising more alkaline and oxic groundwater environments. These assessments reinforce need for future speciation and hydrochemical characterization in elucidating Cr in groundwater in these areas.

Analytical reliability and implications for environmental interpretation

The analytical performance and data-validation results are central to elucidating the environmental implication of the observed geospatial differences . While the calibration results demonstrate a strong linear association over the present working range (Table 1; Figure 1), calibration linearity on its own does not amount to the accuracy and precision of every sample analysis.

The replicate-agreement analysis, however, demonstrates that within-site measurement differences were noticeable at some locality (Section 3.4; Table 3). Thus, where replicate replicates disagree fundamentally, the site average may not represent a sufficiently precise estimate of the underlying water-source level, and small variability in site Cr levels should not mechanically be interpreted as expressive environmental contrasts. Nonetheless, the highest-ranked sites are valuable for categorizing locality that may merit further investigation.

This is predominantly critical in field monitoring, especially when analytical precision and field-sample collection differences could both influence the reliability of geospatial comparisons. Even though the results yielded a strong calibration coefficient, the current dataset thus constitutes an exploratory indication of Cr occurrence , pointing towards more in-depth analytical validation for definitive exposure analysis and regulatory classification.

The differentiation between analytical exclusion and statistical outlier determination must also be clarified. S11B was not included due to its absorbance surpassing the calibration range, and not as a result its computed Cr levels being statistically unusual. This is critical as statistical outlier determination and analytical validity checks tackle diverse issues. The former analyzes the

data behavior within a dataset, while the latter measures whether an observation can be quantified reliably based on an analytical procedure. In the present case, S11Bexclusion was based on the analytical procedure and not because an empirical finding of extreme concentration value.

Associations between chromium, pH and elevation

The exploratory correlation analysis did not establish sufficient significant monotonic associations between Cr and either pH or surface altitude surface altitude (Section 3.6; Table 4), suggesting that neither variable, individually controlled the observed site-level variability in Cr levels. The lack of a significant Cr–pH association is noteworthy given pH is often discussed as a critical factor in explaining Cr transport and adsorption in groundwater systems (Guo et al., 2024; Izbicki et al., 2015).

This seeming variance from literature should not be considered as empirical findings that pH is inconsequential in the Turkana groundwater system. Rather, it demonstrates that a simple monotonic association between pH and the measured Cr levels were not established across the investigated sites. Chromium transport is contingent upon many interacting factors, comprising oxidation–reduction regimes, mineral surfaces, DO, aqueous complexation and the composition of aquifer materials. A single pH measurement may thus be deficient in explaining geospatial variability where these other factors have not yet been determined. In addition, the lack of Cr speciation analyses constraints the extent to which the observed association can be compared with other works that explicitly examined specific Cr species.

Similarly, the absence of a statistically significant chromium–surface elevation association demonstrates that surface altitude surface altitude alone was not a useful predictor of Cr variability within the investigated sites. Altitude can influence groundwater recharge, drainage and hydrogeologic regimes, nonetheless, its effects on water chemistry are also likely to be mediated by local geology, aquifer structure, groundwater flow and residence time. Thus, the result cautions against using topographic surface altitude as a replacement for explicit hydrogeologic profiling.

Marzouki et al. (2025), in their study of groundwater in the semi-arid Guire Basin in Morocco, demonstrated the value of integrating hydrochemical, isotopic and geospatial empirical findings to distinguish geologic and anthropogenic determinants on groundwater quality. Their integrated method constitutes a valuable methodological comparison. It also underscores the limitations of elucidating groundwater chemistry via isolated parameters. The Turkana results similarly indicate that future investigation should combine Cr replicates with a broader set of hydrochemical and hydrogeologic parameters as opposed to being relying on pH or surface altitude surface altitude alone.

Spatial association with the Ngamia exploration benchmark area

The geospatial analysis established an exploratory inverse association between site-level Cr levels and distance from the combined Ngamia benchmark area (Section 3.8; Table 6; Figure 3). The comparison of the nearest and farthest distance groups similarly demonstrated a difference in their Cr distributions. These results suggest that Cr levels were not geospatially independent of geographical positioning relative to the chosen benchmark point within this specific dataset. They constitute a framework for additional

scrutiny of geospatial variability in the broader study area.

Nevertheless, the observed association must not be interpreted as empirical findings that petroleum exploration or activities caused Cr contamination. Distance from the Ngamia benchmark area is a geographical descriptor, and not necessarily a direct indication of exposure to petroleum-related mobilizations. A geospatial association may arise through several complementary frameworks, comprising variability in lithology, groundwater flow, aquifer connectivity, well construction, source type, local land use activities or other geospatially structured environmental regimes. Without hydrogeologic empirical findings and appropriate source-specific chemical tracers, the relative contribution of the possible determinants remains unelucidated.

The local petroleum-development dimension makes the question environmentally pertinent; nonetheless, it does not resolve the source-attribution challenge. Evidence concerning drilling water or other petroleum-related water-quality concerns in the Lokichar Basin remain differentiated from direct empirical findings of Cr contamination of the potable-water sources examined in the present work. So, the Ngamia 1 & 5 analysis should be interpreted strictly as a spatial proximity-based analysis.

The directional analysis constitutes another descriptor of the geospatial variability, even though, its interpretation is severely limited by the unequal number of sample collection sites across the sectors (Section 3.9; Table 7; Figure 4), with some sectors comprised a small number of data, constraining the reliability of sector-specific correlation estimates. In particular, the apparent southwest association utilizes very few sites and may not be treated as robust empirical findings of a directional concentration gradient. So, the sector-specific results are useful for building hypotheses about geospatial variability, but may do not amount to a mechanism of a plume, flow direction or contaminant migration pathway.

An additional limitation is that the geospatial analysis utilized point data from a relatively small number of available water access sites. The mapped pattern therefore measured Cr values at the investigated localities and may not necessarily be interpreted as representing a continuous contamination surface. Interpolation would demand for more extended geospatial coverage.

The key implication of the Ngamia analysis is therefore methodological and hypothesis-generating. It establishes a geospatial association that necessitates further scrutiny through a more targeted research design, and it does not claim a petroleum-related water contamination pathway that will demand incorporating groundwater levels, aquifer lithology, well depth, structural geology, groundwater-flow information and repeated replicates at locality target to distinguish spatial proximity effects from hydrogeologic controls, with additional appropriate benchmark locality and chemical indicators for testing possible petroleum-related influence independent of geographical drivers.

Implications for groundwater monitoring and future research

The results have significance in groundwater-quality monitoring in southeastern Turkana given they demonstrate that Cr occurrence should be evaluated at the level of individual water sources as opposed to being inferred from regional regimes alone. The hydrogeologic differences recorded in Turkana South by Nyaberi et al. (2019a,

2019b) confirms the need for monitoring frameworks that take into account the variability in geologic formations, structural controls and groundwater occurrence . The present findings reinforce an earlier water-quality dimension to these local empirical findings base by establishing geospatial variability in Cr replicates across target potable-water sources.

The present investigation constitutes exploratory empirical findings of Cr occurrence and geospatial variability, nonetheless, the absence of Cr speciation limits regulatory or health-risk interpretation of the present results, as well as reliable source attribution. The results therefore demonstrate that future environmental monitoring should extend beyond detecting and identifying constituent concentration to establishing its chemical form and elucidating its source.

A more comprehensive follow-up investigation should thus have four priorities. First, Cr replicates should be repeated based on a fully documented and validated approach, with confirmation of the Cr fraction measured. Second, Cr speciation should be integrated where technically feasible, primarily to differentiate Cr(III) from Cr(VI). Third, hydrochemical profiling should be extended to encompass parameters particularly pertinent to Cr mobility, such as redox potential, DO, major ions and other fitting geochemical indicators. Fourth, geospatial sample collection should be designed around the hydrogeologic structure of the area, with sufficient coverage and repeated sample collection to analyze temporal differences and test possible source associations.

These imperatives would enable future work to move beyond the descriptive geospatial associations established here towards a more mechanistic understanding of Cr occurrence . They would also constitute the empirical findings needed to evaluate whether specific water sources demand for targeted monitoring or regulatory intervention. Until such confirmation is in place, the present results should be utilized to guide further investigation rather than as a guide to compliance.

Study's Contribution and investigation limitations

The main contribution of this work is therefore its exploratory documentation of Cr occurrence and geospatial differences in target potable-water sources in southeastern Turkana, an area for which the local literature has more often addressed groundwater occurrence , geologic controls and broader water-resource regimes than chromium-specific water quality. By assessing Cr at both observation and site levels and relating site-level replicates to target physicochemical and geographical parameters, the investigation presents important baseline empirical findings for more focused groundwater-quality monitoring in the area.

Nonetheless, a number of limitations mark the strength and scope of this contribution. The cross-sectional sample collection design captures the water conditions during the sample collection campaign and fail to capture seasonal or longer-term variations. Due to limited number and the dispersed nature of the water points the geospatial coverage is limited to the investigated sites and does necessarily not support extrapolation to all potable-water resources in Turkana County. Marked replicate differences undermines fine-scale variability between some sites. Concentrations are documented as total Cr in mg/L; Cr speciation was not measured. Finally, the spatial proximity analysis does not amount to hydraulic connectivity or contaminant source

attribution of the observed water quality parameters.

These limitations do not negate the value of the data, nonetheless, they measure how the reported observations should be interpreted. The investigation is best regarded as a benchmark exploratory analysis that identifies geospatial variability and analytical questions that require follow-up investigations. Its implication lies in identifying a reasoned framework for confirmatory scrutiny and hydrogeochemical investigation, rather than in demonstrating a specific contamination source attribution or human-health effect; reference exceedances are documented as comparisons and not as compliance records.

Conclusion and Recommendations

This investigation documented substantial geospatial variability in measured total Cr across 39 water-source sites in southeastern Turkana County. Site-level averages varied from 0.8070 to 10.0385 mg/L, and all 39 sites surpassed the Kenyan and WHO total-chromium drinking-water value of 0.05 mg/L and the current EU value of 0.05 mg/L; all also surpassed the US EPA value of 0.10 mg/L. Thirty-one sites surpassed the NEMA 1.5 mg/L irrigation-water benchmark, a non-drinking-water standard. Locality and source-typology aggregations demonstrate that enriched values were distributed across the investigated area, even though small and unequal group sizes constrain typology-level inference. The inverse association with distance from the combined Ngamia benchmark point is exploratory and not a claim of petroleum-related source attribution. Because Cr speciation was not conducted, to the findings represent total Cr only. Follow-up work should confirm concentrations based on a fully validated methodology, document QA/QC, including Cr speciation, expanded hydrochemical and hydrogeologic replicates, and repeat sample collection across seasons. Nevertheless, the present results constitute a valuable benchmark for such future confirmatory monitoring, and more a definitive analysis of related health risk or contamination source attribution.

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Author Contributions

MG wrote initial research protocols, conducted laboratory analyses, wrote and revised the manuscript; EWW conceptualized and supervised the project development, execution and documentation; ZMO participated in overall project supervision, reviewed final results and manuscript write up; HA conducted actual field sample collection, coding and transportation to the laboratory; PJ participated in development of initial research protocol;. KAS reviewed final sample preparation methods and oversaw laboratory sample preparations before final analyses; and FSK reviewed final laboratory protocols and supervised laboratory analyses.

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