

Invisible Contaminants, Visible Sources: Spatiotemporal Mapping of Benzene, Toluene, and Xylene and Source Identification in Nakuru Town Groundwater, Kenya.

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ABSTRACT

Urban groundwater in rapidly growing African towns is increasingly threatened by volatile organic compounds, yet forensic source apportionment remains limited. This study investigated the spatiotemporal distribution and sources of benzene, toluene, and xylene (BTX) in Nakuru town, Kenya. Water samples from 26 boreholes across diverse land-use zones were collected during the wet and dry seasons and analyzed by Headspace Solid-Phase Microextraction coupled with Gas Chromatography-Mass Spectrometry (HS-SPME-GC-MS). ArcGIS simple Kriging was used for spatiotemporal mapping, and diagnostic mass ratios toluene/benzene (T/B) and toluene/xylene (T/X) were used for source identification. Seasonal variation was observed; average concentrations surged, with xylene more than doubling from 1.368 µg/L in the wet season to 3.43 µg/L in the dry season, and toluene levels rising from a wet-season average of 0.555 µg/L to 1.383 µg/L in the dry season for positive samples. Additionally, T/X ratio analysis showed that 71.4–83.3% of calculable samples exhibited xylene-dominant signatures (T/X < 0.5). This indicates that Nakuru town's groundwater is primarily impacted by non-petroleum sources, such as industrial solvents, municipal waste leachate, and sewage effluent, rather than solely by petroleum spills. T/B ratios, where detectable, confirmed localized fresh and weathered petroleum inputs. This study establishes a forensic framework for urban groundwater management, recommending that regulatory strategies expand beyond petroleum remediation to include stringent monitoring of industrial solvents and municipal waste discharges to safeguard vital water resources.

Keywords: Benzene, Toluene, Xylene, Source Apportionment, Spatiotemporal Mapping, Diagnostic Ratios.

INTRODUCTION

Groundwater is vital for over 2 billion people worldwide, especially in sub-Saharan Africa where water infrastructure cannot keep up with urban growth (WHO, 2021). In Kenya, many rely on groundwater as their main drinking water source, particularly in growing urban areas like Nakuru (Ministry of Water and Irrigation, 2021). However, this vital resource is increasingly threatened by human activities, as volatile organic compounds (VOCs) emerge as a significant yet frequently overlooked category of pollutants (Maina et al., 2024). Among the VOCs, benzene, toluene, and xylene, collectively referred to as BTX, are classified as priority pollutants due to their high water solubility, environmental mobility, and intrinsic toxicity (ATSDR, 2024).

The contamination of urban aquifers by BTX presents a paradox: these pollutants are invisible, dissolved plumes migrating through the subsurface, yet they originate from highly visible surface human activities. Typically, BTX contamination in groundwater is associated with petroleum-related sources such as leaking underground storage tanks (USTs) at fuel stations or vehicle spills (Nassery et al., 2024). Nevertheless, this assumption oversimplifies

the intricate chemical reality of urban environments. Xylene and toluene are widely used as industrial solvents, paint thinners, and degreasers, and are prevalent in municipal solid waste leachate and sewage effluent (Sauer & Bedford, 2004; Wang et al., 2025). Therefore, distinguishing between new petroleum spills and ongoing industrial or municipal discharges is crucial for effective environmental management. However, this remains a significant analytical challenge.

Environmental forensics employs diagnostic mass ratios and spatiotemporal mapping techniques to trace the sources of these invisible plumes (Nassery et al., 2024). Chemical fingerprints, such as the toluene-to-benzene (T/B) and toluene-to-xylene (T/X) ratios, are especially important. In fresh, unweathered gasoline, toluene generally exceeds benzene ($T/B > 2.0$) and is approximately equal to xylenes ($T/X \approx 1.0$) (Kim et al., 2019; Nassery et al., 2024). In contrast, a xylene-dominant signature ($T/X < 0.5$) strongly suggests non-petroleum sources, such as industrial solvents or landfill leachate. Conversely, a low T/B ratio (< 0.5) indicates a substantially weathered petroleum plume, in which toluene has undergone considerable biodegradation (Chun-yan et al., 2016). When utilized in conjunction with Geographic Information Systems (GIS) for spatiotemporal mapping, these diagnostic ratios allow researchers to visually and chemically associate subsurface contamination plumes with their corresponding surface sources, while also monitoring seasonal hydrological effects on the dilution and migration of contaminants (Aliabad & Alimohammadi, 2025; Cruz et al., 2025).

Despite the widespread prevalence of BTX research globally, forensic source identification for urban aquifers in Africa remains notably limited. In Kenya, current groundwater investigations primarily focus on inorganic contaminants such as fluoride, nitrate, and heavy metals (Maina et al., 2024). Furthermore, most regional VOC research employs single-season evaluations that fail to account for significant seasonal variations driven by tropical wet-and-dry hydrological cycles (X. Zhang et al., 2023). This knowledge gap impedes the development of targeted, evidence-based remediation strategies, as environmental regulators cannot effectively mitigate contamination without understanding whether the principal sources are sudden petroleum spills or continuous industrial and municipal waste discharges.

This study addresses key gaps by examining the spatiotemporal behavior and sources of BTX in groundwater in Nakuru town, Kenya. Using Gas Chromatography-Mass Spectrometry (GC-MS), ArcGIS simple Kriging interpolation, and diagnostic mass ratios, the research aims to quantify seasonal variations in BTX levels across land-use zones, map subsurface plumes relative to surface contamination hotspots, and apply T/B and T/X ratios to distinguish among petroleum, industrial, and municipal pollution sources. The results will establish a new forensic framework for managing urban groundwater in rapidly growing African cities.

METHODOLOGY

Study Area

Nakuru town is Kenya's fifth-largest city (Figure 1), with a population exceeding 570,600 residents (KNBS, 2019), a figure that has likely grown due to recent urban expansion. Located within the Great Rift Valley at $0^{\circ}18'S$, $36^{\circ}04'E$, it sits at an elevation of 1,850 meters above sea level. The region experiences a bimodal rainfall pattern, characterized by long rains from March to May and short rains from October to December, and extended dry seasons from January to March (Kenya Meteorological Department, 2025). It is mainly an agricultural and residential town with various industrial facilities. Notably, it hosts several industries, including manufacturing, construction, and petroleum-related activities in the pipeline zone. The area's aquifer system consists of weathered tuffs, basaltic flows, and alluvial sediments, which exhibit moderate to high hydraulic conductivity and facilitate the downward transport of surface contaminants into groundwater (Kanda & Suwai, 2013). Boreholes serve as the primary water source for domestic and commercial use (Nakuru County Government, 2023).

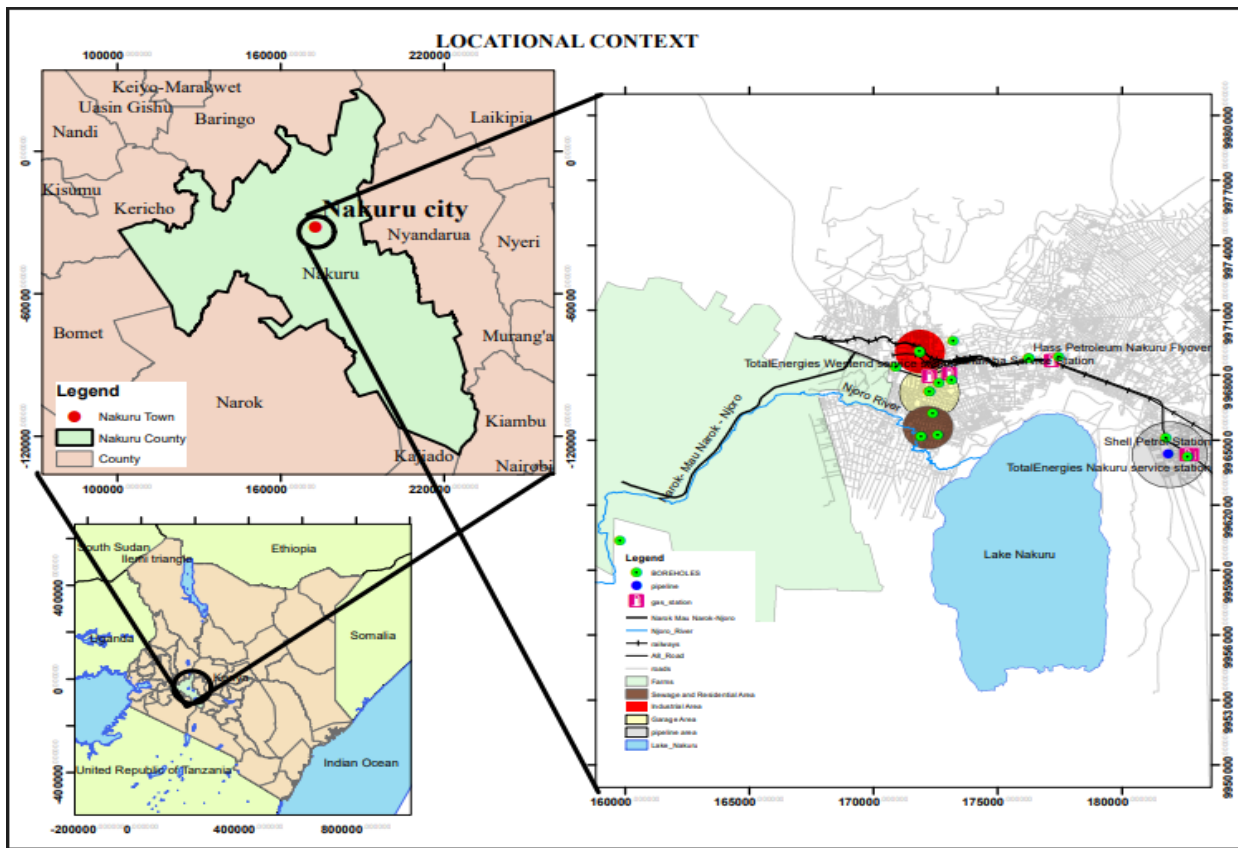


Figure 1: Map of the Study Area

Sampling Design and Collection

A total of 26 operational boreholes were selected using stratified purposive sampling based on land-use classification, including the industrial zone, landfill zone, pipeline infrastructure zone, residential zone, agricultural zone, sewage treatment zone, transport corridor, garages zone, and gas stations retail zone. Borehole depths ranged from 30 to 100 m (Gevera & Onyari, 2025). Water samples were collected and preserved in accordance with USEPA laboratory guidelines (Doug, 2023). Samples were collected in replicate in 40 mL amber glass vials with Teflon-lined caps, filled to overflowing with no headspace, and preserved in a cooler box at 4-6 °C. In situ physicochemical parameters, including temperature, pH, and oxidation-reduction potential (ORP), were measured using a calibrated multi-parameter probe.

Chemicals and Reagents

Throughout this study, analytical-grade standard solutions of benzene, toluene, xylene, methanol, and sodium chloride with purities $\geq 99.9\%$ were used. They were purchased from Sigma-Aldrich through Kobian Scientific Limited in Kenya and used as received, without further purification. Deionized water was used throughout unless otherwise stated.

Instrumentation

This study used a gas chromatography-mass spectrometry (GC-MS) system (Scion 8900) to quantify benzene, toluene, and xylene concentrations in water samples. A handheld Garmin GPS device recorded zonal and borehole coordinates.

Sample Pretreatment and GC-MS Analysis

Headspace solid-phase microextraction (HS-SPME) was used for sample preparation. A 75 μm DVB/CAR/PDMS SPME tri-layered fast uptake fiber was exposed to the sample headspace at 40°C for 28 minutes with agitation, then thermally desorbed in the GC inlet at 250°C for 5 minutes. Elution was then performed on a capillary column using helium as the carrier gas at a flow rate of 1.2 ml/minute. Oven temperatures were programmed as follows: 40°C for 3 minutes, ramped at 8°C/minute to 300°C, then held for 5 minutes. MS detection was performed in electron ionization mode at 70 eV, with a scan range of m/z 35–300.

Quality Control and Assurance

Method optimization and validation were conducted before laboratory testing, yielding specific values and conditions (Table 1) used as experimental parameters. Moreover, reagents of analytical grade were employed throughout the process. Blanks were prepared and analyzed following the same protocols and reagents as the actual samples. All working standards were prepared within the analytical range for each compound via serial dilution. Additionally, all analyses were carried out in triplicate to ensure the validity and reproducibility of the results.

Table 1: Method Optimization and Validation Values

COMPOUND	LOD	LOQ	R ²	RSD (%)	SPIKE RECOVERIES (%)	EXTRACTION TIME (minutes)	NaCl (w/v) (%)
			0.99	< 15	80-120	28	12
Benzene	0.031	0.095					
Toluene	0.033	0.1					
Xylene	0.035	0.105					

Spatiotemporal Mapping

The geographic coordinates of twenty-six boreholes were recorded using a handheld Garmin GPS device with an accuracy of approximately ± 3 meters. Spatiotemporal distribution maps illustrating BTX concentrations during the dry and wet seasons were generated using ArcGIS simple Kriging methodology with a root mean square error of 1.76 to 1.89 for all the interpolations.

Source Identification

Source identification used two methods: spatial correlation with human activity hotspots and diagnostic mass ratios.

Spatial Correlation

Interpolated contamination plumes were integrated into land-use maps to visually and statistically link subsurface, invisible plumes to surface sources.

Diagnostic Ratios

The toluene-to-benzene (T/B) and toluene-to-xylene (T/X) ratios were calculated to identify potential contamination sources and assess plume weathering.

RESULTS AND DISCUSSION

Physicochemical Parameters

The movement, persistence, and natural breakdown of BTX compounds in groundwater depend on the local hydro-physicochemical conditions. Measurements of borehole water during the dry and wet seasons provided essential insights into the mechanisms underlying the observed dynamic behavior of BTX in this study.

Temperature

Groundwater temperatures remained relatively stable, averaging 24.98 °C (Table 2). At these temperatures, microbial metabolic rates are adequate to sustain year-round natural attenuation. Furthermore, measured temperatures determine the specific Henry's Law constants for BTX, highlighting the potential for volatilization (Song et al., 2025).

The pH

Groundwater pH at the site ranges from 6.21 to 7.88 (Table 2) and falls within the optimal range of 6.0 to 8.5 for microbes responsible for hydrocarbon degradation (Song et al., 2025). Consequently, pH does not constitute a limiting factor for intrinsic bioremediation at this location. Fluctuations in contaminant concentrations are more likely driven by redox conditions and transport mechanisms than by microbial inhibition.

Oxidation-Reduction Potential

The ORP values listed in Table 2, ranging from 219 to 570 mV, suggest mostly aerobic conditions within the aquifer. These favorable redox conditions facilitate active BTX biodegradation, which helps explain the observed variations in compound concentrations (Brown et al., 2024).

Table 2: Physicochemical Properties

S/No	Zones	Boreholes	TEMP (° C)		pH		ORP (mV)	
			Wet	Dry	Wet	Dry	Wet	Dry
1	Industrial	BH 01	22.3	23.8	7.73	7.68	284	268
		BH 02	20.1	20.9	6.37	6.33	563	551
		BH 03	24.3	24.7	7.82	7.8	261	219
2	Landfill	BH 04	26.2	26.7	7.81	7.8	304	300
		BH 05	23.9	24.1	7.53	7.54	341	327
		BH 06	24.3	24.6	7.69	7.64	338	346
3	Pipeline	BH 07	21.3	22.8	7.65	7.48	401	389
		BH 08	30.3	29.4	7.21	7.18	404	400
4	Residential	BH 09	21.3	21.7	7.13	7.04	360	356
		BH 10	21.5	22.0	7.88	7.79	263	240
		BH 11	22.3	22.8	7.62	7.64	271	346
5	Agricultural	BH 12	27.8	27.7	6.73	6.65	542	522
		BH 13	42.9	43.1	6.31	6.28	420	412
		C BH	25.3	26.0	6.51	6.51	456	441
6	Sewage	BH 15	24.9	25.2	6.51	6.47	439	440
		BH 16	20.1	23.1	6.37	6.4	568	553
		BH 17	23.9	24.4	6.81	6.92	570	561
7	Transport	BH 18	27.4	26.4	6.78	6.69	344	331
		BH 19	26.4	26.6	6.23	6.21	509	502
		BH 20	27.9	28.1	6.44	6.79	423	440
8	Garage	BH 21	21.9	22.7	7.2	7.02	381	370
		BH 22	22.7	22.8	6.3	6.14	400	407

9	G. Stations	BH 23	23.6	24.2	6.9	7.01	333	378
		BH 24	23.2	24.6	7.81	7.62	511	510
		BH 25	22.6	23.3	7.26	7.09	428	423
		BH 26	24.2	24.9	7.78	7.92	498	511

Occurrence and Spatiotemporal Distribution of BTX Compounds

Qualitative Confirmation Results

GC-MS qualitative analysis confirmed BTX in the borehole water samples. Although minor retention time (RT) shifts were observed between the standards and the environmental samples, as illustrated in Table 3, such variations are common in complex environmental matrices due to matrix effects, slight column ageing, or co-eluting interferences (Raposo & Barceló, 2021). O-xylene was used as a representative of other isomers in the samples. Consequently, the mass-to-charge ratios (m/z) for all detected compounds matched their respective standards, providing definitive qualitative confirmation of the analytes (EPA, 2023).

Table 3: GC-MS Standards' and Samples' RT and m/z Results

Standards			Samples		
Compound	RT (+/- 0.150)	m/z	Compound	RT	m/z
Benzene	1.406	78	Benzene	1.407	78
Toluene	2.680	92	Toluene	2.683	92
Xylene	4.251	106	Xylene	4.250	106

A significant seasonal variation was observed in the concentration profiles.

Wet Season.

Figure 2 illustrates the varying degrees of attenuation among the BTX compounds. Xylene appears at trace to moderate concentrations, toluene stays at trace levels, and benzene is consistently not detected (BDL), highlighting the aerobic aquifer's specific bio-filtering capacity during high-recharge conditions.

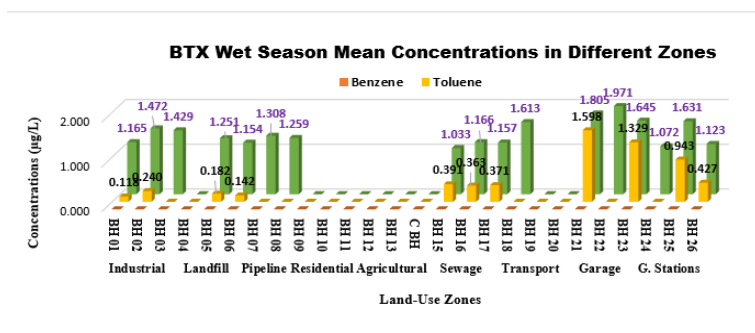


Figure 2: BTX Wet Season Borehole Mean Concentrations

Benzene

Benzene exhibits comparatively high solubility in water, approximately 1,780 mg/L at 25⁰ C relative to heavier hydrocarbons. Furthermore, it has a moderate Henry's law constant (5.5×10^{-3} atm.m³/mol), facilitating volatilization into the unsaturated soil zone under appropriate hydrogeological conditions (Z. Zhang et al., 2025). High rainfall recharge during the wet season significantly increases groundwater volume and flow velocity. This

creates a strong dilution effect, dispersing trace organic inputs to levels far below analytical detection limits. In addition, the natural attenuation of benzene is heavily governed by the redox conditions of the aquifer, which characterize the study area. The combination of active aerobic biodegradation and favorable groundwater temperatures of 20.1-26.2 °C across most zones creates an efficient natural bio-filter that removes benzene from the aqueous phase.

These results indicate that the short-term cancer risk from benzene in borehole water in Nakuru town during the rainy season stays within safe regulatory standards. Nevertheless, ongoing monitoring is recommended to capture possible seasonal changes in contaminant movement.

Toluene

Toluene concentrations ranged from 0.118 µg/L to 1.598 µg/L, with an average of 0.555 µg/L in positive samples. The highest level was found in the garage zone (1.598 µg/L), suggesting improper disposal of spent solvents, wash water from mechanical workshops, and unregulated effluent discharge into the subsurface environment. Additionally, toluene was detected in two boreholes in the industrial zone (0.118 µg/L and 0.240 µg/L) and in another borehole in the landfill zone (0.182 µg/L). Toluene is widely used as an industrial solvent in products like paint thinners, adhesives, and mechanical degreasers. Although municipal landfills mainly produce biogenic gases such as methane and carbon dioxide, they also receive household and commercial hazardous waste, including discarded paint cans, cleaning solvents, and automotive fluids that contain these compounds (Gomes et al., 2023). Leaching from these disposed products creates a varied leachate plume rich in mono-aromatic hydrocarbons such as toluene. These concentrations do not indicate an immediate public health threat, but they serve as a critical early warning indicator of localized groundwater contamination (WHO, 2021).

Xylene

Xylene was the predominant BTX compound detected in groundwater. Concentrations ranged from 1.072 µg/L to 1.971 µg/L, with an average of 1.368 µg/L in positive samples. These results were limited to areas linked with petroleum handling, industrial activities, waste management, and transportation. The highest levels were observed in the garage zone, with boreholes 21 and 22 measuring 1.805 µg/L and 1.971 µg/L, respectively. These environments are characterized by high fuel-handling volumes and extensive use of xylene-rich solvents for mechanical degreasing and parts cleaning. The findings indicate that petroleum handling challenges and improper disposal of spent solvents are major point sources.

Xylene's persistence in the environment, relative to benzene and toluene, depends on its molecular structure and physicochemical characteristics, which allow it to evade natural biofiltration in aquifers. Specifically, xylene has two methyl groups attached to the aromatic ring, creating substantial steric hindrance that physically slows microbial aerobic dioxygenases produced by environmental microbes from attacking the aromatic ring (El-Naas et al., 2014). Hence, in the highly aerobic Nakuru town aquifer with ORP > 250 mV, xylene degrades at a fraction of benzene's rate.

Secondly, xylene is more hydrophobic than benzene and toluene. This increased hydrophobicity causes xylene to strongly partition into and sorb onto soil organic matter in the vadose zone. Although this slows its downward migration, it also forms a secondary source of contamination. As groundwater flows past these contaminated soil matrices, xylene slowly and continuously desorbs into the water, sustaining long-term groundwater contamination even if primary surface spills are halted (R. E. Ismail et al., 2023). Finally, xylene has significantly lower aqueous solubility (106–180 mg/L) and a higher organic carbon partition coefficient ($\log K_{oc}$ 2.31–2.44) than benzene (1,780 mg/L and $\log K_{oc}$ 1.78). Unlike benzene, which readily dissolves and disperses in percolating recharge water, xylene sorbs more strongly to soil organic matter in the unsaturated zone, forming a persistent secondary contamination source that continuously desorbs into the saturated aquifer over time (Xu et al., 2026).

The xylene levels in borehole water samples were below the WHO guideline of 500 µg/L. Based on the data, consuming this water is unlikely to pose health risks or exceed safety limits for residents in Nakuru town.

Dry Season

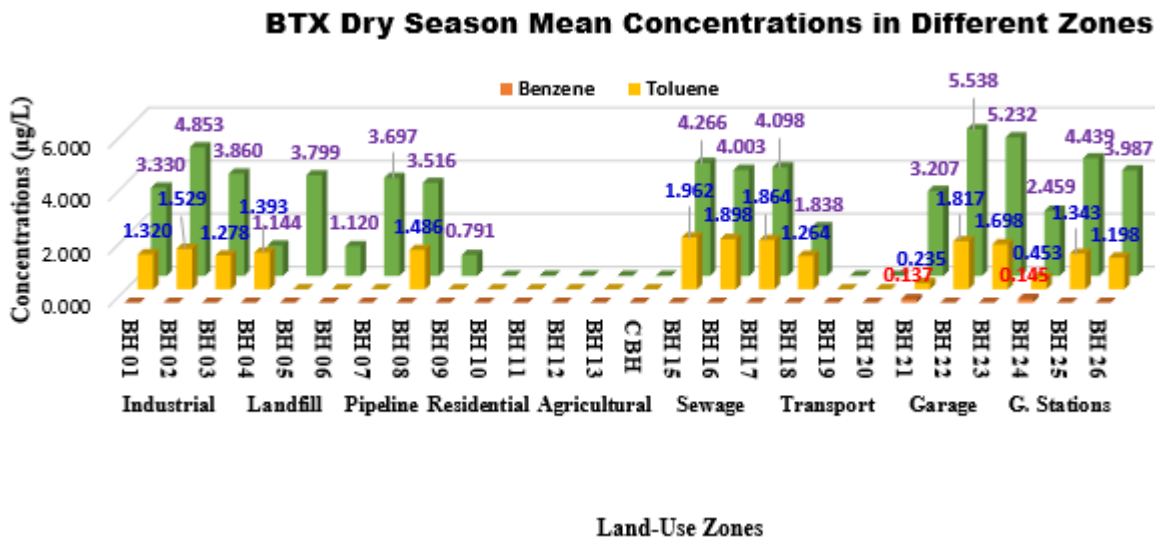


Figure 3 clearly illustrates the seasonal rise and the spatial pattern of the BTX profile during the dry season. Unlike the wet season, it shows detectable benzene, a consistent increase in toluene, and a significant spike in xylene, highlighting the impact of reduced recharge dilution and vadose-zone desorption due to water-table drawdown.

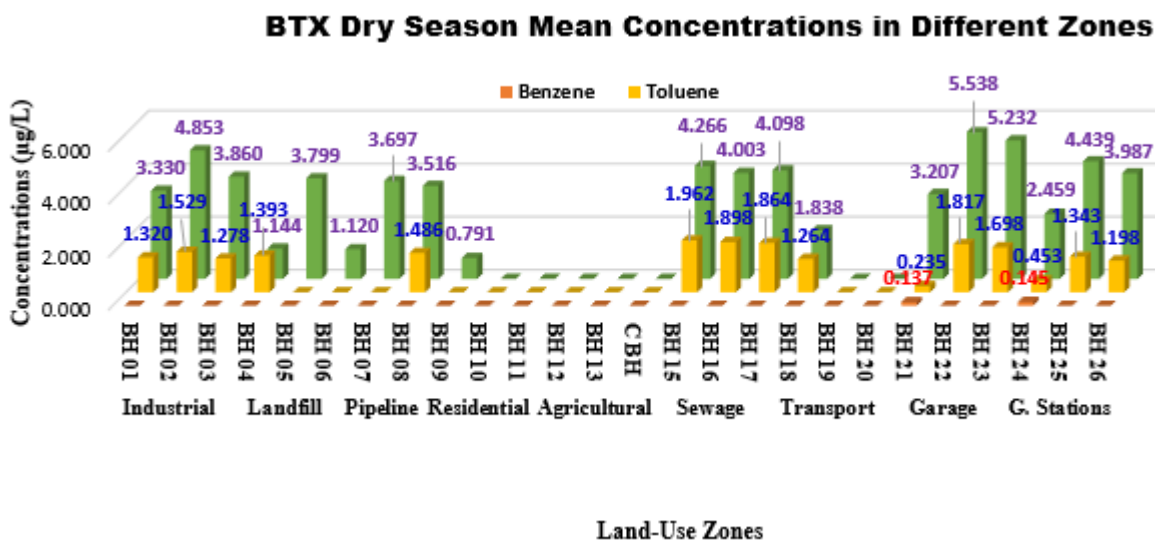


Figure 3: BTX Dry Season Borehole Mean Concentration

Benzene

The dry season analysis found trace amounts of benzene in two zones. Although most of the 26 boreholes were below the detection limit, measurable benzene levels were observed in the garage zone (0.137 µg/L) and in a borehole near a gas station (0.145 µg/L).

This strong spatial correlation indicates that the main sources of benzene in Nakuru town are directly linked to petroleum activities. The minor trace detection in these boreholes suggests improper disposal of petroleum waste

and possibly micro-leaks from underground storage tanks or fuel spills, confirming that the contamination is solely petro-genic (C. Yang et al., 2012).

The physicochemical data showing high positive ORP values indicate that groundwater stays strongly oxidizing during the dry season. Under such conditions, benzene is rapidly degraded via aerobic biodegradation in boreholes with BDL results. Local microbial communities efficiently mineralize benzene as it reaches the saturated zone, utilizing dissolved oxygen to prevent its buildup to dangerous levels (Han et al., 2025).

The benzene results during the dry season do not pose an immediate public health threat, but they act as a vital early warning of localized petro-genic contamination. Seasonal changes underscore urban aquifers' susceptibility to concentration shifts driven by groundwater withdrawals.

Toluene

The shift from the wet to the dry season caused significant changes in groundwater quality, including increased toluene concentrations and detections in previously unaffected areas.

Toluene was detected in 15 of the 26 sampled boreholes, with detection frequency rising from 42.3% in the wet season to 57.7% in the dry season. Average concentrations increased from 0.555 $\mu\text{g/L}$ to 1.383 $\mu\text{g/L}$. During the dry season, five boreholes that were below detection limits in the wet season showed new positives: industrial zone borehole 03 at 1.278 $\mu\text{g/L}$, pipeline zone borehole 08 at 1.486 $\mu\text{g/L}$, transport corridor zone borehole 18 at 1.264 $\mu\text{g/L}$, garages zone borehole 22 at 1.817 $\mu\text{g/L}$, and borehole 24 near a gas station at 0.453 $\mu\text{g/L}$.

When rainfall stops, water recharge ends, and continued borehole groundwater extraction builds up dissolved solids and organic matter in the remaining water (Cavelan et al., 2025). Furthermore, lowering the water table can expose previously submerged contaminated soil layers to oxygen fluctuations, disrupting the sorption-desorption balance and potentially releasing adsorbed toluene into the groundwater (R. Ismail et al., 2020). This mechanism explains why zones that were BDL in the wet season suddenly registered positive detections as the water table receded. Detecting contamination, especially in the dry season, shows how urban aquifers are susceptible to human-caused pollutants. This underscores the importance of ongoing, seasonal monitoring to accurately assess groundwater quality (Yatoo et al., 2024).

The highest dry-season concentration, 1.962 $\mu\text{g/L}$, is very low compared to the WHO provisional guideline of 700 $\mu\text{g/L}$ for drinking water (WHO, 2021). While the dry-season results do not indicate an immediate threat to public health, they serve as a vital early warning system.

Xylene

During the dry season, xylene exhibited concentration spikes and a considerable expansion in its spatial distribution compared with the rainy season. This offers valuable insights into xylene's hydrophobic properties and highlights the profound impact of dry-season hydrogeological drawdown on urban aquifers.

The detection rate of xylene rose from 65.4% during the wet season to 73.1% in the dry season. Measured concentrations ranged from 0.791 to 5.538 $\mu\text{g/L}$, averaging 3.43 $\mu\text{g/L}$ in positive boreholes.

The dry season uncovered new positive detections in areas previously below the detection limit (BDL) during the wet season, including borehole 09 in the residential zone, which measured 0.791 $\mu\text{g/L}$. This wider spatial distribution suggests the xylene contamination plume is larger than the wet-season data indicate, although it is considerably masked by hydrological dilution during high-recharge periods (C. Zhang, 2019). As the water table drops, moisture levels in the capillary fringe fluctuate, prompting desorption. This causes xylene previously adsorbed onto soil particles to be rapidly released into groundwater. These observations indicate that the borehole is drawing water directly from this highly contaminated capillary fringe, causing concentrations to rise (Wu et al., 2024).

The rise during the dry season indicates continued xylene input from sewage line leaks, fuel spills, and potential micro-leaks from underground storage tanks (UTSs). This contaminant-saturated soil creates a substantial secondary source that is more active during the dry season. However, xylene levels are comfortably below the WHO safety limit of 500 $\mu\text{g/L}$ for xylene in drinking water (WHO, 2021). Nevertheless, dry-season data point to a significant environmental issue, showing that shallow groundwater is heavily contaminated with hydrophobic organic pollutants (Chen et al., 2022).

Spatial Mapping and Plume Identification

The ArcGIS simple Kriging interpolation maps clearly showed how BTX compounds move beneath the surface, linking unseen dissolved plumes to recognizable human-made sources on the surface. The spatial models indicated that the contamination was concentrated in specific areas, rather than spread evenly throughout the aquifer.

Benzene

Figure 4 depicts the interpolated spatial distribution of benzene concentrations in Nakuru town during the dry season. The map delineates contamination patterns, with non-detectable levels (BDL) in most of the zones in the study area. Elevated concentrations were identified in the garage zone (0.137 $\mu\text{g/L}$) and in the borehole near fuel stations within the central business district (0.145 $\mu\text{g/L}$).

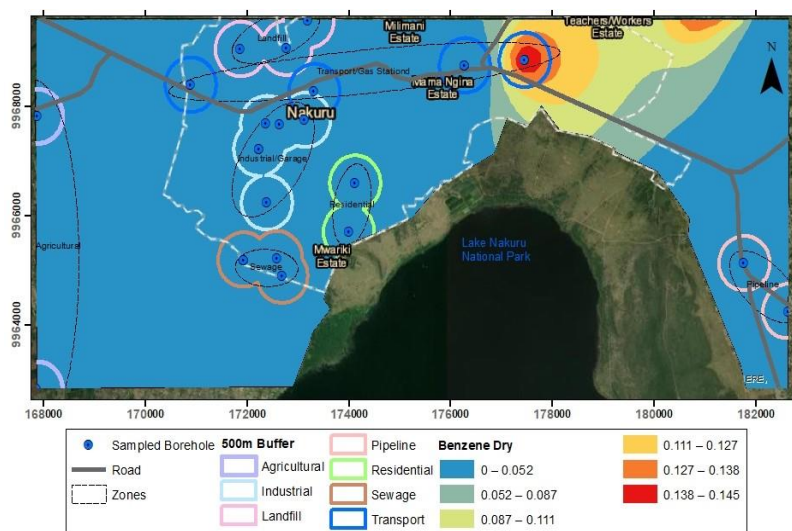


Figure 4: Map Showing Benzene Distribution across Study Area

The area surrounding the garage demonstrated the highest benzene concentration at 0.145 $\mu\text{g/L}$, forming a distinct contamination plume covering approximately 1.5 km^2 . This concentration suggests a probable point source, most likely linked to petroleum waste disposal and the challenges of petroleum handling. The control borehole, located outside the town's activities, offers a baseline, confirming that the benzene detected originates from anthropogenic activities in Nakuru town rather than natural regional sources (Usher et al., 2004).

Toluene

Toluene showed clear seasonal variations in Nakuru town's groundwater, being present in both wet and dry seasons.

Wet Season

During the wet season, levels varied from non-detectable (BDL) at the edges to a peak of 1.598 $\mu\text{g/L}$ in the garages zone. See Figure 5 below.

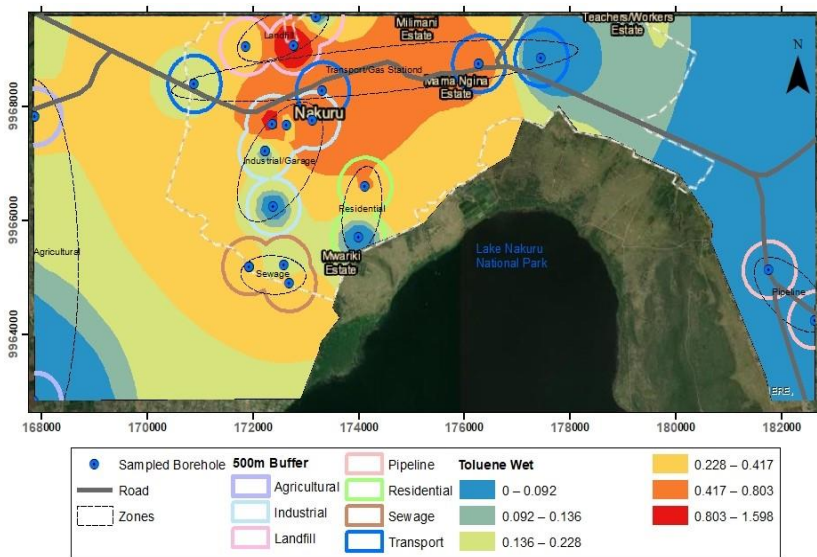


Figure 5: Map Showing the Spatial Distribution of Toluene during the Wet Season

Three contamination hotspots have been identified: the sewage zone, landfill area, and garage/industrial zone. These locations are characterized by waste-disposal activities and are situated in densely populated regions. The control borehole exhibited non-detectable toluene levels, confirming the absence of regional background contamination. This suggests that the toluene concentrations observed in Nakuru town are predominantly attributable to anthropogenic activities (Lapworth et al., 2017).

Dry Season

The dry season highlighted significantly higher concentrations and more distinct contamination plumes. The peak concentration was 1.962 µg/L in the sewage treatment area, as illustrated in Figure 6 below.

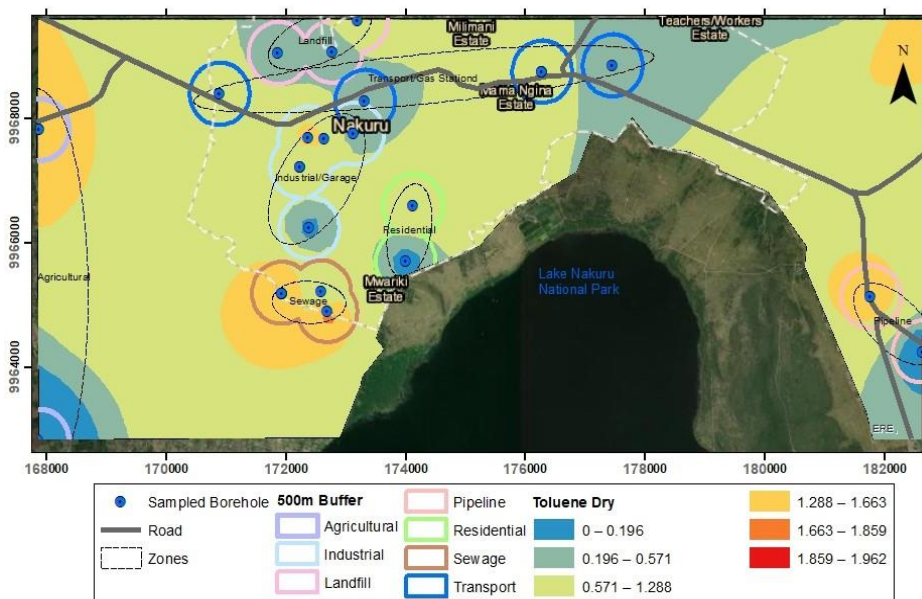


Figure 6: Map Showing the Spatial Distribution of Toluene during the Dry Season

The primary contamination hotspot showed concentrations ranging from 1.264 to 1.962 µg/L (orange-red zone), indicating a notable point source. Potential sources include petroleum storage, industrial activities, auto repair shops, or waste disposal sites (Fei-Baffoe et al., 2024). Ongoing contamination observed in sewage treatment plants,

landfills, industrial sites, and garage areas across seasons indicates a continuous point source rather than temporary pollution (Chira et al., 2024).

The persistent failure to detect toluene at the Summat control borehole across both seasons supports the conclusion that any detected toluene likely stems from anthropogenic activities in Nakuru town rather than regional background sources.

Xylene

The spatial distribution and concentration levels of xylene varied considerably. Its year-round presence suggested environmental persistence, moderate water solubility, and complex biodegradation mechanisms (Adnani et al., 2020).

Wet Season

Figure 7 illustrates the interpolated spatial distribution of xylene concentrations during the wet season, highlighting a localized hotspot at the high-plume garage area.

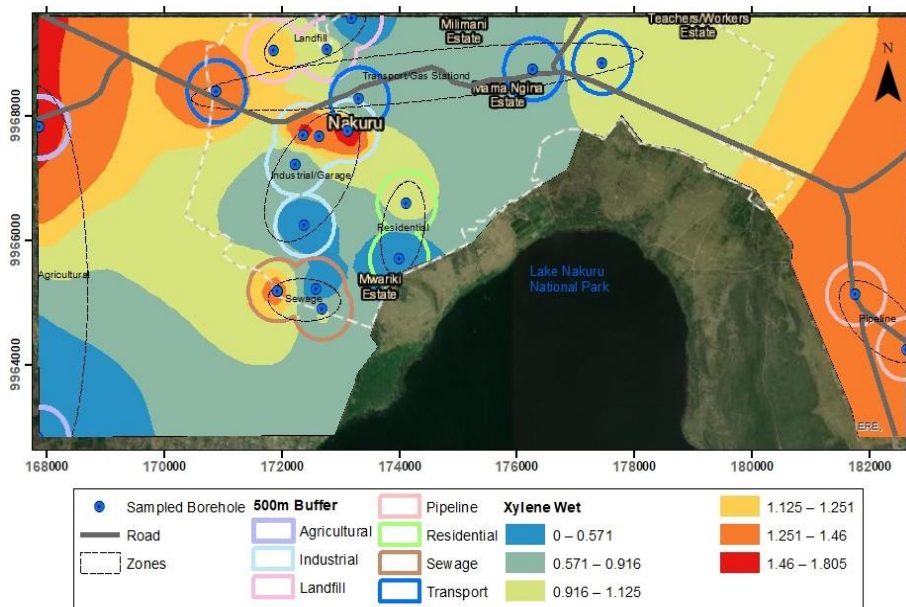


Figure 7: Map Showing the Spatial Distribution of Xylene during the Wet Season

The central region, encompassing industrial and garage zones, displayed concentrations ranging from 1.072 to 1.745 $\mu\text{g/L}$. The pipeline area recorded levels up to 1.308 $\mu\text{g/L}$. During the wet season, concentrations were relatively uniform, producing gentle gradients that suggest rainfall facilitated dilution and promoted lateral dispersion (Du et al., 2025).

The Summat control borehole (BDL) confirmed the absence of regional background contamination and verified that the concentrations detected in Nakuru town are anthropogenic in origin (Li et al., 2019).

Dry Season

Figure 8 shows the distribution of xylene during the dry season, indicating elevated concentrations and more distinct contamination plumes, with a maximum value of 5.232 $\mu\text{g/L}$ observed within the garage zone.

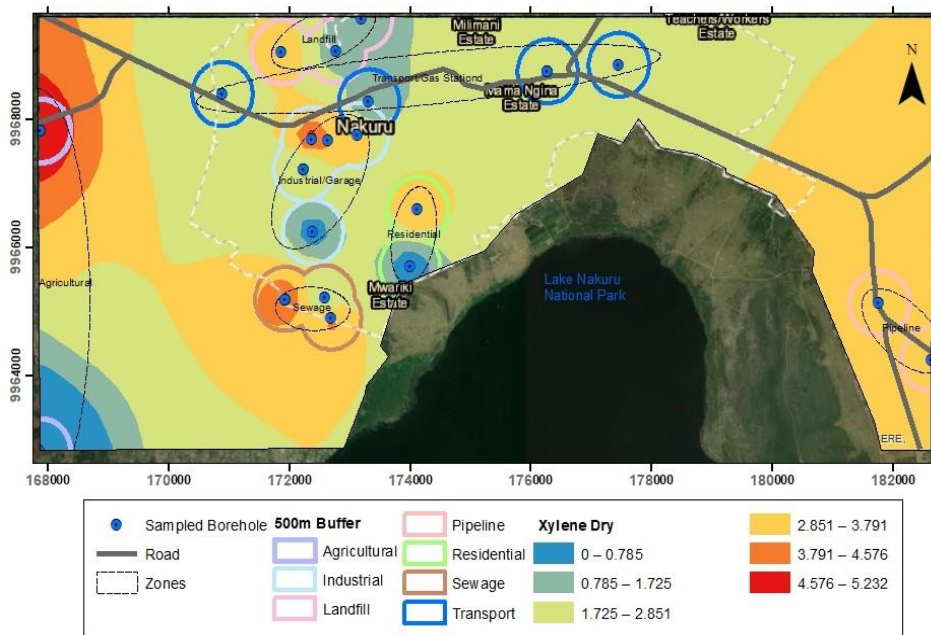


Figure 8: Map Showing the Spatial Distribution of Xylene during the Dry Season

The municipal center, including industrial, landfill, and transportation corridor areas, showed moderate to high levels (3.619–4.444 $\mu\text{g/L}$), indicating diffuse urban pollution and commercial activity. Meanwhile, the pipeline and garage zones had concentration plumes ranging from 4.95 to 5.232 $\mu\text{g/L}$, pointing to possible point sources related to petroleum handling.

The consistent detection of BDL at the Summat control borehole across both seasons confirms that the detected xylene originates from anthropogenic activities within Nakuru town, rather than from regional background sources (Li et al., 2019).

These maps offered a crucial baseline for comprehending the environmental origins of pollutants. Spatial analysis showed that BTX pollution was unevenly distributed, with notable hotspots linked to human activities such as industrial operations, landfills, and petroleum handling. Comparing data across seasons was imperative, as it revealed contamination trends that single-season investigations would have missed.

Source Identification

To identify the sources of the unseen plumes, diagnostic toluene-to-benzene (T/B) and toluene-to-xylene (T/X) ratios were calculated. However, because benzene was frequently undetectable, T/B ratios were calculated for only two samples during the dry season, limiting T/B applications across the study area.

Toluene-to-Benzene (T/B) Ratios

The two calculated T/B ratios were 1.72 and 3.13, indicating point-source pollution. The ratio of 3.13, observed in a borehole near a petrol station, indicates fresh, unweathered gasoline, with toluene naturally exceeding benzene (Meng & Li, 2025). Conversely, the ratio of 1.72 found in a borehole in a garage zone suggests a mixed source or a moderately weathered petroleum plume, in which toluene biodegradation has begun (US EPA, 2015; Y. J. Yang et al., 2005).

The detection of toluene, with benzene remaining below detection limits in most regions, indicates that the source is likely associated with industrial activities and waste disposal rather than petroleum fuel blends (Sadiki et al., 2005).

Toluene-to-Xylene (T/X) Ratios

The T/X ratios provided a more comprehensive forensic dataset, with values ranging from 0.073 to 1.217 across both seasons. Analyzing the distribution of these ratios revealed essential insights into the sources of contamination. Although T/X ratios are frequently employed as diagnostic indicators of contaminant sources, they are not entirely conservative. Differential biodegradation and volatilization of toluene and xylenes can modify the ratio along the groundwater flow path. Therefore, spatial variations in T/X ratios should be interpreted as the integrated outcome of both source composition and subsurface attenuation, rather than as sole indicators of source disparities (Y. J. Yang et al., 2005).

Xylene-Dominant Plumes ($T/X < 0.5$)

Most calculated T/X ratios (71.4% in the wet season and 83.3% in the dry season for the calculable boreholes) were below 0.5, with some as low as 0.073. In environmental forensics, a T/X ratio < 0.5 indicates xylene-rich, non-petroleum sources like industrial solvents, municipal waste leachate, and sewage effluent (Qu et al., 2022). The results show that these low T/X values mainly correlate with sewage treatment and industrial areas. The boreholes with a high T/X ratio (0.5) are presumably located at the point source, whereas those with a low ratio (0.073) are farther from the pollution sources (Nassery et al., 2024).

A smaller group of samples showed T/X ratios ranging from 0.5 to 1.0, with one sample reaching 1.217. These elevated ratios, mainly found in the garage zone, sewage treatment zone, and a borehole near a petrol station, suggest a greater contribution from toluene, which aligns with recent petroleum inputs or a mixed-source profile in which petroleum hydrocarbons and solvents coexist (Chen et al., 2022).

CONCLUSION

This study investigated the spatiotemporal distributions and sources of benzene, toluene, and xylene (BTX) in Nakuru town's groundwater, linking subsurface contamination to surface activities. It offers a forensic method for analyzing pollution in rapidly growing African cities. Seasonal variation showed higher BTX levels in dry seasons, emphasizing the role of seasonal recharge in dispersing contaminants. ArcGIS simple Kriging interpolation mapping revealed uneven, localized contamination.

Using diagnostic mass ratios improved understanding of contamination sources. The widespread very low toluene-to-xylene (T/X) ratios indicate Nakuru town's groundwater is mainly affected by xylene-rich sources other than petroleum, such as industrial solvents, waste leachate, and sewage, not just fuel spills.

The study offers a valuable approach to understanding groundwater contamination by combining chemical assessment, spatial analysis, temporal patterns, and source identification. Its findings can support environmental monitoring, groundwater protection, land-use planning, and pollution-control strategies in Nakuru town. Regular monitoring of BTX concentrations and identification of high-risk areas are recommended. Collaboration among environmental agencies, local authorities, industries, and communities may further strengthen prevention and remediation efforts, helping protect groundwater quality and public health.

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Conflict of Interest

The Kabarak University Research Ethics Committee (KUREC) approved this study in accordance with national research ethics guidelines. The approval covered environmental sampling and laboratory analysis. Research authorization was subsequently granted by the National Commission for Science, Technology and Innovation (NACOSTI) under license number NACOSTI/P/26/4187447, permitting fieldwork within Nakuru town.

Data Availability

The datasets generated and analyzed during this study (geospatial coordinates) are available from the corresponding author upon reasonable request.

Supplementary materials, analytical calibration curves, and raw instrumental data are archived in the Kabarak University Institutional Repository for academic reference.

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