

ORIGINAL RESEARCH

Spatial Non-Compliance and Ecosystem Risk of Service-Station Proliferation in a Densely Populated Tropical Megacity District: A GIS-Based Assessment of Funa, Kinshasa (DR Congo)

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ABSTRACT

Background: Unregulated proliferation of open-air service (petrol) stations in Kinshasa, Democratic Republic of the Congo, poses ecosystem and public-health risks through soil, water and air pollution, fire, and chronic exposure to carcinogenic volatile hydrocarbons.

Objective: This study assessed compliance of station siting with separation-distance standards and quantified the resulting spatial risk in the Funa pilot district.

Methods: Twenty-four stations were geolocated by GPS (2019–2023); Euclidean distances to the nearest dwelling, school, church and hospital, and to the nearest neighbouring station, were computed in a GIS and analysed by one-way ANOVA with Tukey HSD, Pearson correlation, regression and principal component analysis, then synthesised in a composite Spatial Encroachment Risk Index (SERI).

Results: Mean station-to-dwelling distance was 21.8 ± 7.8 m, with no station meeting the 50 m minimum; mean distances to schools (157.8 ± 48.5 m), churches (127.9 ± 42.2 m) and hospitals (286.7 ± 103.0 m) all fell below the 500 m standard (0% compliance), and only 20.8% met the 500 m inter-station criterion. Distances differed by receptor class ($F(3,92) = 77.07$, $p < 0.001$, $\eta^2 = 0.715$), and newer stations were sited closer to receptors (hospitals $r = -0.745$, $p < 0.001$); 21 of 24 stations were High or Very High risk.

Conclusion: Total non-compliance demonstrates an urgent need for a specific siting decree and an accompanying layout manual to protect the urban ecosystem and population health.

Introduction

Rapid, unplanned urbanisation in tropical megacities has intensified the collision between hazardous infrastructure and sensitive land uses, raising environmental-health risks that weak regulatory regimes struggle to contain.¹⁻³ Among such infrastructure, service (petrol) stations occupy a

uniquely problematic position: legally classified as hazardous installations, they store and dispense volatile, flammable and carcinogenic hydrocarbons in the very heart of the residential fabric, and their number has grown explosively across the developing world as motorisation outpaces planning. In Kinshasa, the capital of the Democratic Republic of the Congo (DR Congo) and one of the largest cities in Africa, pollution risks are

rising, exacerbated by non-compliance with standards and by the unregulated construction that lines the city's arterial roads. The siting of high-risk infrastructure has therefore become a pressing question of urban environmental governance.

The principal hazards of service stations are well characterised in the contemporary environmental literature, and they operate through several distinct pathways. Through the air pathway, refuelling losses, dispenser leaks and tank breathing emit benzene, toluene, ethylbenzene and xylene (BTEX), a suite of monoaromatic hydrocarbons of which benzene is a confirmed human carcinogen; measured BTEX concentrations are highest at the forecourt and decay steeply with distance, approaching urban background only beyond roughly 100–200 m.⁴⁻⁷ Through the water pathway, leaking underground storage tanks (USTs) release dissolved hydrocarbons that migrate into shallow aquifers and form persistent plumes which are costly and slow to remediate.⁸ Through the soil and fire pathway, surface spills and accidental ignition generate total-petroleum-hydrocarbon contamination and the risk of fire or explosion, hazards that are amplified where stations cluster at high-footfall crossroads.⁹⁻¹¹

These multi-medium pathways converge on vulnerable human receptors. A substantial body of exposure-assessment research shows that residents, schoolchildren, worshippers and hospital patients located within approximately 100 m of a station experience elevated chronic benzene exposure and a measurable increment in lifetime cancer and neurological risk.¹²⁻¹⁵ The hazard is not confined to a single source: where several emitting facilities cluster in one neighbourhood, cumulative exposure can exceed the limit attributable to any one of them.¹⁶ Consequently, both the spacing of stations from receptors and the spacing of stations from one another emerge as central, policy-actionable determinants of neighbourhood-scale risk.

To evaluate these risks at the scale of a city, the field has converged on geographic-information-system (GIS) methods. Euclidean-distance analysis, multicriteria

suitability evaluation and distance-decay assessment are now standard tools for judging siting compliance, mapping exposure surfaces and delineating risk zones.¹⁷⁻²⁰ Compliance is benchmarked against protective separation distances and against ambient air-quality limits, and integrated, sustainability-oriented assessment frameworks increasingly embed such criteria so that siting decisions internalise their environmental cost.^{21,22}

Against this international benchmark, the regulatory framework in DR Congo is inadequate. The Hydrocarbons Code and its implementing regulations address station siting only in general terms; there is no specific decree dedicated to service stations, and the single quantitative reference — a 2017 ministerial circular note addressed to provincial hydrocarbons divisions — recommends a setback of only 30 m from dwellings. This figure lies well below the 50–100 m dwelling minimum and the 500 m public-facility distance enforced by comparator African states such as Cameroon and Madagascar. In practice, building permits for stations are granted in the same manner as for ordinary infrastructure, with responsibilities fragmented across the ministries of urban planning, land affairs, infrastructure and hydrocarbons, so that no single authority is accountable for siting safety; comparable governance gaps have produced unsafe filling-station clustering and weak enforcement in other African and developing-country cities.^{1,2}

For Kinshasa specifically, the existing evidence base documents rapid unplanned growth and rising environmental pressure on air, soil and the shallow aquifer that supplies much of the population.^{3,23} Journalists have repeatedly raised concerns about the environmental impact of the city's service stations. Yet, despite this attention, no peer-reviewed study has quantified the spatial risk of service-station siting in Kinshasa, and earlier Congolese work on the subject has remained descriptive. There is therefore neither a measured baseline against which to judge compliance nor an analytical instrument with which to prioritise intervention.

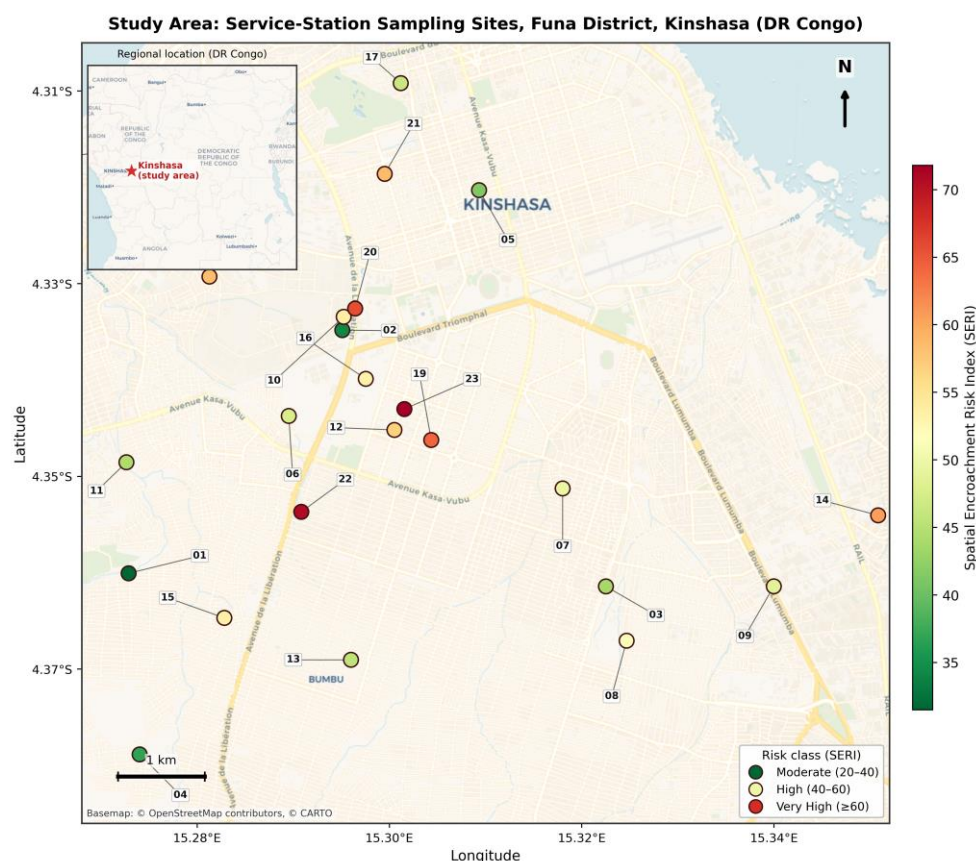


Figure 1. Study-area map of Funa District, Kinshasa (DR Congo), showing the 24 service-station sampling sites colour-coded by Spatial Encroachment Risk Index (SERI) over an OpenStreetMap basemap. The inset locates Kinshasa within DR Congo. Basemap © OpenStreetMap contributors, © CARTO.

The present study addresses this gap directly. Using the Funa pilot district as a case study, it (i) inventories and geolocates the district's service stations, (ii) quantifies their Euclidean separation from dwellings, schools, churches and hospitals and from one another, (iii) tests these distances against regional and international standards using inferential statistics and multivariate analysis, and (iv) integrates the results into a composite Spatial Encroachment Risk Index that ranks stations by risk. The novelty of the work is twofold: it provides the first quantitative, standard-referenced spatial risk assessment of service stations in Kinshasa, and it introduces a transferable risk index designed to support evidence-based regulation. The study area and the spatial distribution of the sampled stations are shown in Figure 1.

Materials and Methods

Study Design and Setting

This was a cross-sectional, georeferenced environmental survey — in effect a spatial census — of service stations and their surrounding sensitive receptors. The analytical approach followed the GIS Euclidean-distance and

multicriteria framework widely adopted for fuel-station risk evaluation,^{17,19} adapted to the data realistically obtainable in an open-air, dense-urban African setting. Rather than attempting direct pollutant measurement, the study used separation distance as a validated proxy for exposure, on the basis that pollutant concentration, fire risk and groundwater vulnerability all decline monotonically with distance from the source.^{4,24}

The study was conducted in the Funa District of Kinshasa, DR Congo (approximate centroid 4.34° S, 15.30° E), a densely populated pilot district that encompasses communes including Bandalungwa, Bumbu, Kalamu, Kasa-Vubu, Makala, Ngiri-Ngiri and Selembao. The district is traversed by paved arterial roads, which are the preferred siting corridors for stations because they guarantee vehicle access and visibility, and by watercourses that constitute a fragile ecosystem and a recharge pathway to the shallow aquifer from which much of the population draws drinking water. As shown in Figure 1, the 24 stations are distributed along these arteries across the district, frequently at or near major crossroads. The full inventory of sites is provided in Table 1.

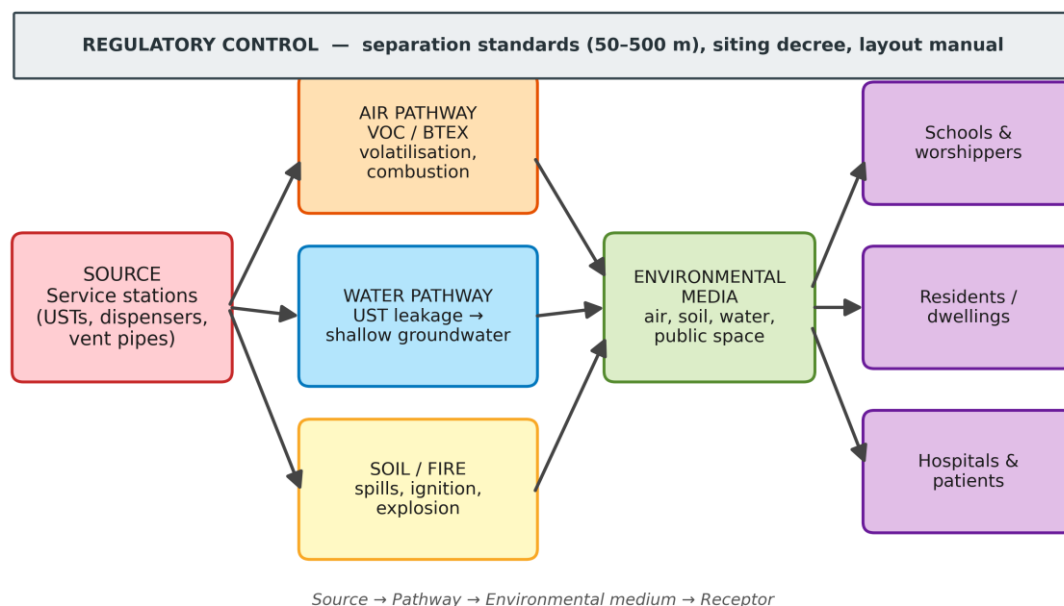


Figure 2. Conceptual framework of service-station ecosystem risk: source → pathway (air, water, soil/fire) → environmental medium → receptor, bounded by the regulatory-control layer. Created by the authors.

Materials, Samples, and Data Sources

All operational service stations within the district boundary were enumerated and geolocated using a handheld GPS receiver during three field campaigns. The first, in November 2019, established the initial census and included direct field (tape) measurement of dwelling setbacks for approximately fifteen stations. The second, in November 2021, re-surveyed the district in conjunction with a parallel study. The third, in 2023, completed the inventory and updated receptor positions. For each station, the geographic coordinates of the nearest school, church and hospital were recorded; for dwellings, the 2019 field measurements were complemented by high-resolution satellite remote sensing in December 2019 to verify and extend the setback data. The year of installation of each station was established from the field inventory cross-checked against historical satellite imagery. The final analytical dataset comprised $n = 24$ stations, each described by five separation distances and an installation year, as summarised in Table 1.

Experimental Variables and Analytical Procedures

Mapping and distance computation were performed in a GIS environment (ArcGIS). All point coordinates were projected to a metric reference system before analysis so that distances were expressed in true metres. For each station, the Euclidean (straight-line) distance to the nearest dwelling, school, church and hospital, and to the nearest neighbouring station, was calculated. To visualise dwelling encroachment, a 50 m buffer corresponding to the lower bound of the regional dwelling standard was generated around each station and overlaid on high-resolution imagery; stations whose buffer intersected occupied dwellings were flagged as non-compliant. The distance-decay logic underpinning

this proxy is consistent with receptor-gradient studies of fuel and waste facilities.^{20,24}

Compliance was assessed against a hierarchy of standards. For dwellings, the DR Congo circular-note setback of 30 m and the regional African minimum of 50–100 m (as applied in Cameroon, Madagascar and France) were used. For public facilities — schools, hospitals and places of worship — and for the distance between stations, the 500 m criterion mandated by the Cameroonian siting decree was adopted as the most explicit and widely cited regional benchmark. Standard-referenced index construction of this kind is well established in environmental quality assessment.^{25,26} The standards used and the measured compliance are presented together in Table 2.

Data Analysis

All analyses were conducted at a significance level of $\alpha = 0.05$. Distributions were first screened for normality (skewness and kurtosis) and for homogeneity of variance before parametric testing. Separation distances across the four receptor classes (dwelling, school, church, hospital) were compared by one-way analysis of variance (ANOVA) with Tukey's honestly-significant-difference (HSD) post-hoc test, and the eta-squared (η^2) statistic was computed as the effect size. The association between installation year and each separation distance was quantified by Pearson product-moment correlation with exact p-values to three decimal places, and the dwelling-distance trend by ordinary-least-squares regression. The multivariate covariance structure of the five distance parameters was examined by principal component analysis (PCA) on standardised variables, a technique widely used to extract dominant gradients in multi-parameter environmental data.²⁷⁻²⁹ Finally, a composite Spatial Encroachment Risk Index (SERI, 0–100) was constructed for each station as a weighted sum

of normalised standard exceedances across the five parameters, with weights reflecting receptor sensitivity and pathway severity (dwelling 0.30; hospital 0.20; school 0.20; inter-station 0.20; church 0.10); the cumulative-index logic follows established environmental and exposure scoring systems.¹⁶ For each parameter the normalised exceedance was computed as $\max(0, (S - d)/S)$, where d is the measured distance to the nearest receptor and S the applicable standard, so that a station meeting the standard scores 0 and one at zero distance scores 1; index scores were classified as Low (<20), Moderate (20–<40), High (40–<60) or Very High (≥ 60). Because the study involved neither human subjects nor biological sampling, ethical approval was not required. The complete statistical output is reported in Table 3.

$$\text{SERI} = \left[\sum w_j \cdot \max(0, (S_j - d_j) / S_j) \right] \times 100 \quad (1)$$

where w_j is the weight of parameter j , d_j the measured distance to the nearest receptor and S_j the applicable standard; a station meeting the standard scores 0 and one at zero distance scores 1.

Results

The 24 service stations and their characteristics are detailed in Table 1. As shown in Figure 1, the stations were distributed across seven communes of the Funa District, predominantly in high-density residential and commercial-junction land uses, and were installed over a two-decade period from 2003 to 2023. The conceptual basis for the risk pathways evaluated in this study — linking the station as a source, through air, water and soil/fire pathways and environmental media, to the exposed receptors, and bounded by the regulatory-control layer whose weakness is the focus of the analysis — is set out in Figure 2.

Table 1. Characteristics of the 24 service-station sampling sites in Funa District, Kinshasa (GPS-geolocated 2019–2023). SERI = Spatial Encroachment Risk Index.

Site	Commune	Year	Lat (°S)	Lon (°E)	Dominant land use	SERI	Class
FS-01	Makala	2003	4.3601	15.2729	Dense residential	31.5	Moderate
FS-02	Ngiri-Ngiri	2006	4.3348	15.2951	Residential / market	34.2	Moderate
FS-03	Kalamu	2008	4.3614	15.3225	Commercial / residential	43.7	High
FS-04	Makala	2009	4.3789	15.2740	Dense residential	36.8	Moderate
FS-05	Selembao	2010	4.3203	15.3093	Peri-urban residential / slope	41.4	High
FS-06	Bandalungwa	2011	4.3437	15.2895	Mixed residential / arterial road	47.7	High
FS-07	Kasa-Vubu	2012	4.3513	15.3180	Commercial core / junction	49.5	High
FS-08	Bumbu	2013	4.3671	15.3247	High-density residential	51.3	High
FS-09	Kalamu	2014	4.3614	15.3400	Commercial / residential	48.7	High
FS-10	Ngiri-Ngiri	2015	4.3334	15.2952	Residential / market	53.6	High
FS-11	Bandalungwa	2016	4.3485	15.2727	Mixed residential / arterial road	44.3	High
FS-12	Ngiri-Ngiri	2016	4.3452	15.3005	Residential / market	56.7	High
FS-13	Kasa-Vubu	2017	4.3690	15.2960	Commercial core / junction	45.6	High
FS-14	Kalamu	2018	4.3540	15.3508	Commercial / residential	60.6	Very High
FS-15	Selembao	2018	4.3647	15.2828	Peri-urban residential / slope	53.5	High
FS-16	Bumbu	2019	4.3399	15.2975	High-density residential	53.2	High
FS-17	Ngiri-Ngiri	2019	4.3092	15.3012	Residential / market	46.3	High
FS-18	Bandalungwa	2020	4.3293	15.2813	Mixed residential / arterial road	58.4	High
FS-19	Bandalungwa	2020	4.3462	15.3043	Mixed residential / arterial road	64.1	Very High
FS-20	Kalamu	2021	4.3326	15.2964	Commercial / residential	65.7	Very High
FS-21	Selembao	2021	4.3186	15.2995	Peri-urban residential / slope	58.6	High
FS-22	Kasa-Vubu	2022	4.3537	15.2908	Commercial core / junction	70.7	Very High
FS-23	Bumbu	2022	4.3430	15.3016	High-density residential	71.8	Very High
FS-24	Makala	2023	4.3179	15.2606	Dense residential	59.4	High

The measured separation distances are reported against the regulatory standards in Table 2 and displayed in Figure 3. As detailed in Table 2, the mean station-to-dwelling distance was only 21.8 ± 7.8 m, ranging from 9.9 to 37.8 m; no station (0%) met the 50 m regional minimum, and only 16.7% (4 of 24) met even the lenient 30 m setback recommended by the DRC circular note, meaning that the overwhelming majority of stations directly abut occupied homes. The mean distance to the

nearest school was 157.8 ± 48.5 m, to the nearest church 127.9 ± 42.2 m, and to the nearest hospital 286.7 ± 103.0 m; every one of these means fell far below the 500 m public-facility standard, producing 0% compliance across all three public-receptor classes. The nearest neighbouring station averaged 382.5 ± 141.9 m, and only 20.8% of stations achieved the 500 m inter-station distance, indicating pervasive clustering along the district's arterial corridors (Figure 3).

Table 2. Mean separation distances of service stations from sensitive receptors versus regulatory standards (n = 24). Status: ✓ = compliant, ✗ = non-compliant for the cohort mean.

Parameter	Mean $\pm$ SD (m)	Range (m)	Reference standard	Comp. (%)	Status
Nearest dwelling	21.8 ± 7.8	9.9–37.8	50 m (regional); 30 m (DRC)	0.0	✗
Nearest school	157.8 ± 48.5	79.9–266.1	500 m (Cameroon decree)	0.0	✗
Nearest church	127.9 ± 42.2	25.6–187.2	500 m (public facility)	0.0	✗
Nearest hospital	286.7 ± 103.0	101.6–482.2	500 m (public facility)	0.0	✗
Other station	382.5 ± 141.9	146.3–686.7	500 m (inter-station)	20.8	✗

Separation distance differed significantly among the four receptor classes (one-way ANOVA $F(3,92) = 77.07$, $p < 0.001$), and the effect was large: the eta-squared value of 0.715 indicates that receptor type alone explained roughly 72% of the variance in separation distance. As reported in Table 3 and visualised by the Tukey letters in Figure 3, the post-hoc test (critical honest-significant difference 46.1 m) placed dwellings (group a)

significantly closer than schools and churches (group b), which were in turn significantly closer than hospitals (group c); schools and churches did not differ significantly from one another. The ordering confirms that the most intimate and numerous receptor, the home, bears the greatest proximity burden, while larger and fewer facilities such as hospitals are comparatively, though still inadequately, better separated.

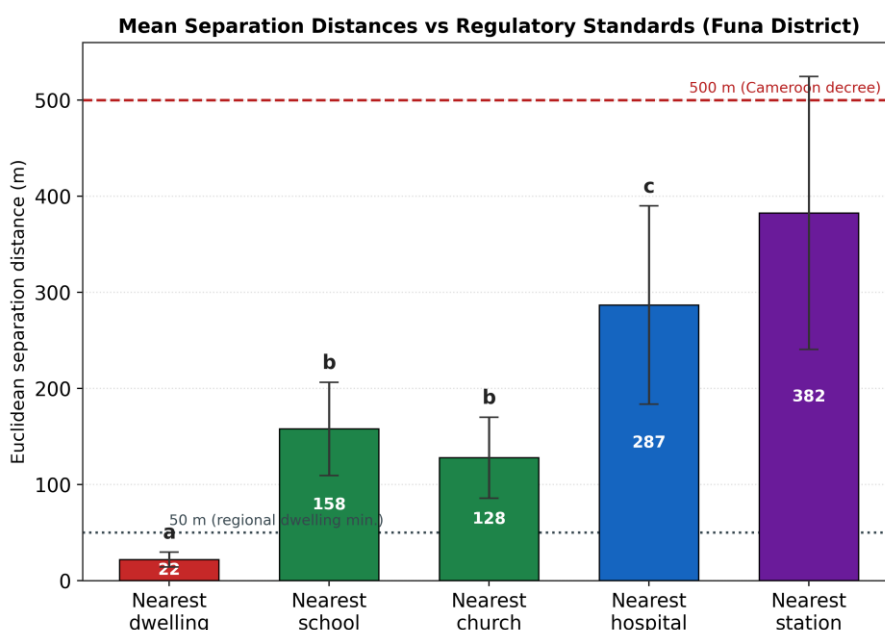


Figure 3. Mean Euclidean separation distances ($\pm$ SD) of service stations from receptors versus regulatory standards. Bars not sharing a Tukey letter differ at $p < 0.05$; dashed line = 500 m public-facility standard, dotted line = 50 m dwelling minimum.

Installation year was negatively and significantly correlated with separation distance for every receptor

class except inter-station spacing, as detailed in Table 3. The correlation was strongest for hospitals ($r = -0.745$, p

< 0.001), followed by dwellings ($r = -0.622$, $p = 0.001$), schools ($r = -0.500$, $p = 0.013$) and churches ($r = -0.443$, $p = 0.030$); the inter-station distance showed a weaker, non-significant trend in the same direction ($r = -0.390$, $p = 0.060$). Ordinary-least-squares regression of dwelling distance on installation year yielded a slope of -0.881 m yr^{-1} ($R^2 = 0.387$, $p = 0.001$), so that each additional year

of the district's expansion brought newly installed stations on average almost one metre closer to the nearest home. This pattern of progressive temporal encroachment is shown in Figure 4, where the downward trend lines for all receptor classes are evident.

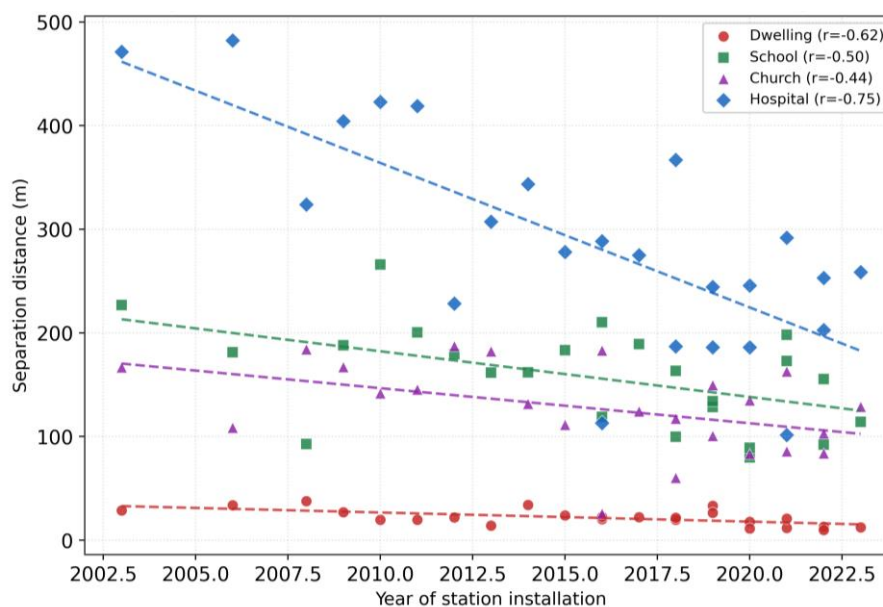


Figure 4. Temporal encroachment: separation distance versus year of installation with ordinary-least-squares trend lines. All receptor classes show declining separation for more recently installed stations.

Table 3. Statistical analysis of service-station separation distances: one-way ANOVA with Tukey HSD across receptor classes, Pearson correlation of distance with installation year, and PCA loadings on the five standardised distance parameters.

(a) One-way ANOVA across receptor classes and Tukey HSD groupings

Receptor	Mean (m)	Tukey group	ANOVA result
Dwelling	21.8	a	$F(3,92) = 77.07$
School	157.8	b	$p < 0.001$
Church	127.9	b	$\eta^2 = 0.715$
Hospital	286.7	c	HSD = 46.1 m

Means not sharing a Tukey letter differ at $p < 0.05$.

(b) Pearson correlation of separation distance with installation year

Parameter	r (vs year)	p-value	Interpretation
Dwelling	-0.622	0.001	Newer stations closer
School	-0.500	0.013	Newer stations closer
Church	-0.443	0.030	Newer stations closer
Hospital	-0.745	< 0.001	Newer stations closer
Inter-station	-0.390	0.060	Trend (ns)

(c) Principal component loadings (PC1 + PC2 explain 62.9% of variance)

Parameter	PC1 (43.0%)	PC2 (19.9%)
Dwelling	-0.527	+0.675
School	-0.692	-0.166
Church	-0.685	-0.335
Hospital	-0.774	+0.365
Inter-station	-0.573	-0.514

Linear regression of dwelling distance on year: slope = -0.881 m yr^{-1} , $R^2 = 0.387$, $p = 0.001$.

Principal component analysis of the five standardised distance parameters extracted a first component that explained 43.0% of the total variance and on which all

five parameters loaded negatively and strongly (Table 3 and Figure 5), confirming a single dominant proximity, or encroachment, gradient that orders the stations from

comprehensively well-sited to comprehensively poorly-sited. The second component (19.9% of variance) contrasted dwelling and hospital setbacks against inter-station spacing, and together the first two components accounted for 62.9% of the variance, as the biplot in Figure 5 illustrates. The inter-parameter correlation matrix, presented in Figure 6, showed the strongest

positive associations between hospital and dwelling distance ($r = 0.42$) and between hospital and school distance ($r = 0.48$), indicating that stations relatively far from one receptor tended to be relatively far from the others as well — that is, siting quality is a coherent station-level property rather than a receptor-specific accident.

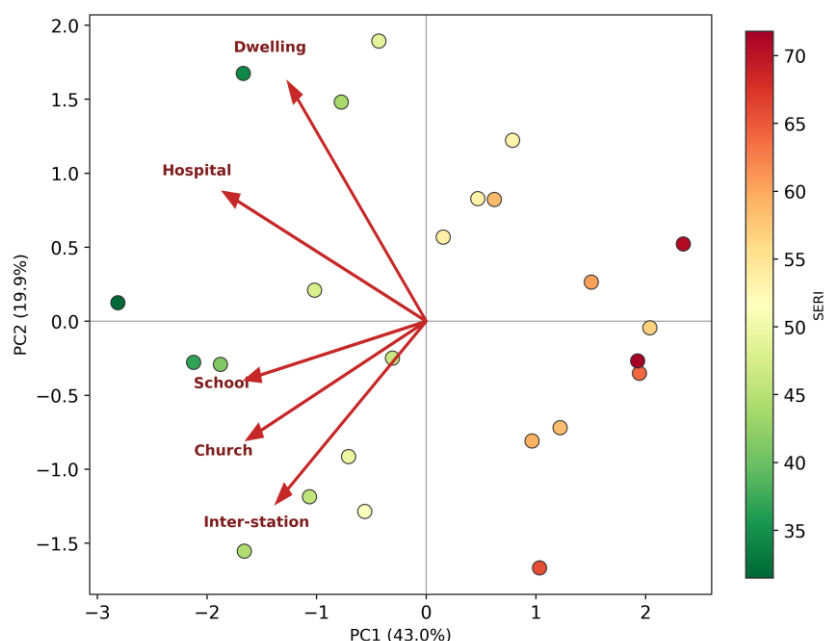


Figure 5. Principal component analysis biplot of the five standardised separation parameters. Points are stations coloured by SERI; red vectors are parameter loadings.

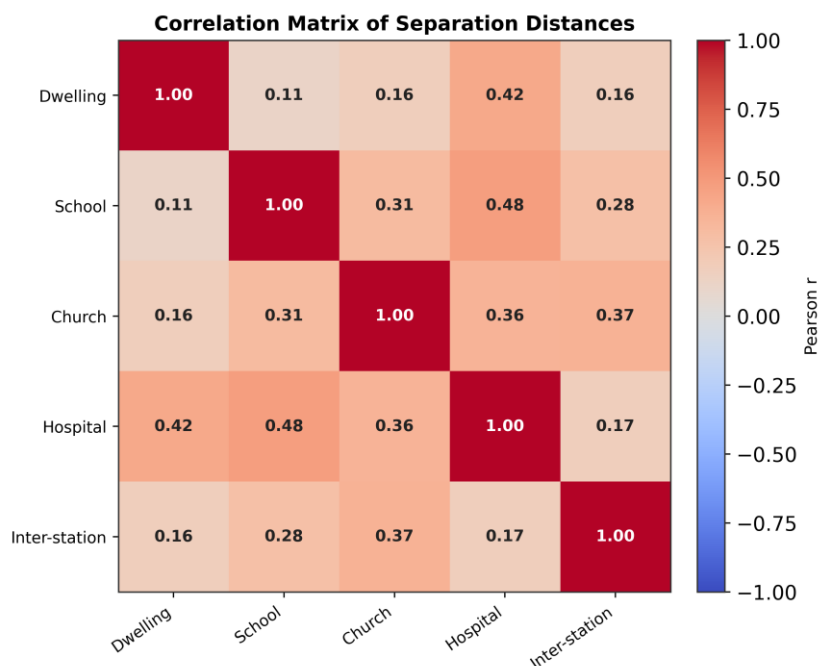


Figure 6. Pearson correlation matrix of the five separation-distance parameters across the 24 service stations.

The composite Spatial Encroachment Risk Index averaged 52.0 ± 10.7 across the cohort, placing the average station squarely in the High-risk band. As ranked in Figure 7, of the 24 stations 5 were classified as Very High risk, 16 as High and 3 as Moderate, with none falling

in the Low category; the per-station scores and classes are also listed in Table 1. The highest-risk stations combined sub-15 m dwelling setbacks with sub-100 m distances to a public facility, and were concentrated among the most recently installed sites at the busiest

commercial junctions, consistent with the temporal-encroachment trend. The index thus condenses the multidimensional compliance failure documented above

into a single ranked metric suitable for prioritising regulatory action.

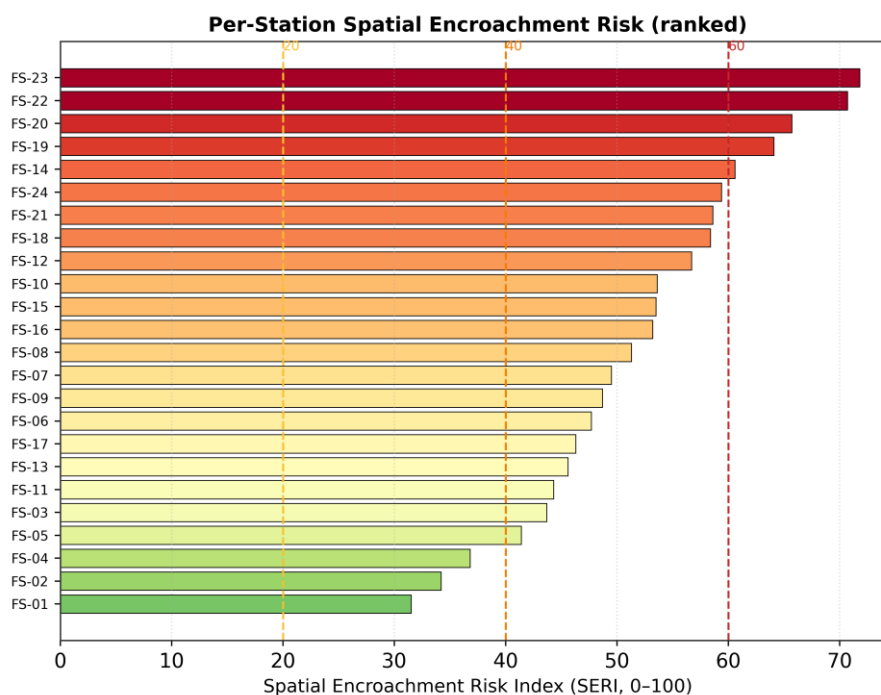


Figure 7. Per-station Spatial Encroachment Risk Index (SERI, 0–100), ranked from lowest to highest. Threshold lines: 20 (Low/Moderate), 40 (High), 60 (Very High).

Discussion

The central finding of this study is unambiguous: not a single service station in the Funa District complies with the separation-distance standards applied by comparator African states, and 21 of the 24 stations fall in the High or Very High risk classes (Figure 7). The mean station-to-dwelling distance of 21.8 m is less than half the 50 m regional minimum and lies well within the 100 m radius over which chronic benzene exposure and indoor vapour intrusion have repeatedly been shown to elevate health risk.^{12,13,14} Because forecourt BTEX concentrations decay to urban background only beyond roughly 100–200 m,^{4,5} the great majority of Funa residents living beside these stations are effectively inside the chronic-exposure zone, a conclusion consistent with distance-based exposure studies in which proximity to fuel and emission sources is the leading predictor of urban pollutant burden.^{15,20}

The large ANOVA effect size ($\eta^2 = 0.715$) and the ordered Tukey grouping reported in Table 3 (dwelling < school $\approx$ church < hospital) reflect an intuitive but consequential urban geography. The home — the most numerous and most continuously occupied receptor — is also the closest to the hazard, while hospitals, being fewer and occupying larger parcels, are somewhat better separated. Yet even the best-separated class, hospitals at a mean of 287 m, remains far short of the 500 m public-facility standard. This finding lends quantitative support to the long-standing concern that ambient air quality around poorly sited urban facilities compromises the

very institutions meant to protect health. The systematic non-compliance also mirrors the experience of other African cities, where permit deregulation has produced dangerous filling-station clustering and weak enforcement.^{18,19}

The temporal analysis adds a dynamic dimension that a static survey cannot reveal, and it is arguably the study's most policy-relevant result. The significant negative correlations between installation year and separation distance — strongest for hospitals ($r = -0.745$) and dwellings ($r = -0.622$), as shown in Figure 4 — demonstrate that the siting problem is actively worsening rather than stabilising: each successive cohort of stations is squeezed closer to sensitive receptors as the remaining road frontage is consumed. This is the spatial signature of a market governed by demand and supply rather than by planning, in which the ease of obtaining permits to occupy public space drives station multiplication, a dynamic documented in studies of rapid, weakly regulated urban land markets.^{1,2} The regression slope of approximately one metre of dwelling buffer lost per year implies that, absent intervention, the buffer will continue to erode toward the physical limit of the road reserve.

The PCA and correlation structure (Figure 5 and Figure 6) reinforce the interpretation that risk in Funa is general rather than receptor-specific. The dominant principal component loaded on all five distance parameters together, so a poorly sited station tends to be poorly sited with respect to every receptor and to its neighbours simultaneously. This coherence is precisely

what justifies the composite SERI as a management tool, since siting quality behaves as a single latent station-level property that can be meaningfully summarised in one score; comparable principal-component and weighted-index approaches are now standard for collapsing multi-parameter environmental data into actionable indices.²⁷⁻²⁹ By integrating weighted exceedances into a single 0–100 index, the SERI (Figure 7) converts a multidimensional compliance failure into a ranked priority list that regulators can act on directly, with the five Very High stations forming the obvious first targets for mitigation or enhanced engineering controls.

The environmental implications extend well beyond air quality. In a city where shallow groundwater is the principal drinking-water source for millions of inhabitants, the clustering of stations with sub-25 m dwelling setbacks over a vulnerable aquifer raises a serious risk of well contamination from leaking underground tanks, consistent with the UST-plume and petroleum-hydrocarbon groundwater literature^{8,30} and with distance-gradient evidence that groundwater quality degrades sharply near contaminant sources.²⁴⁻²⁶ The preferential siting of stations at crossroads — the city's natural gathering, transit and stopping points — concentrates fire and explosion risk exactly where human density and traffic peak.^{11,21} The fact that no catastrophic accident has yet occurred in the study area should be read as latent rather than absent risk; the spatial conditions for a high-consequence event are already in place.

These results expose a fundamental governance gap. The DR Congo Hydrocarbons Code, notably its Article 157, and the 2017 circular note address station siting only superficially, and the 30 m setback the circular recommends is itself below any protective threshold identified in the comparative literature. The fragmentation of mandates across the ministries responsible for urban planning, land, infrastructure and hydrocarbons means that permits can be issued without any single authority taking responsibility for siting safety, a pattern that elsewhere has been shown to undermine enforcement and produce ineffective urban policy.^{1,2} The evidence assembled here — total non-compliance, worsening encroachment and a quantified risk ranking — provides exactly the empirical basis required to justify and design a specific siting decree, modelled on the Cameroonian instrument, that fixes enforceable distances (at least 50–100 m from dwellings, at least 500 m from public facilities and between stations) and is operationalised through a layout manual specifying setbacks, tank standards, drainage and routine monitoring.

Several limitations should be acknowledged. The study is confined to a single pilot district, so the absolute figures should not be extrapolated to the whole of Kinshasa without further survey, although the underlying governance drivers are city-wide and the qualitative pattern is likely general. Euclidean distance is a deliberately conservative exposure proxy that does not capture prevailing wind direction, barrier effects, traffic

emissions or the actual throughput of individual stations; direct measurement of BTEX in air, total petroleum hydrocarbons in soil and dissolved hydrocarbons in groundwater would substantially refine the exposure estimate,^{9,10,23} and repeated seasonal sampling would capture temporal variability. The SERI weights, although informed by the relative toxicity of the pathways and the sensitivity of the receptors, are necessarily based on expert judgement and would benefit from formal sensitivity analysis and local calibration. These limitations notwithstanding, the convergence of several independent analyses — descriptive, inferential, multivariate and index-based — on the same conclusion lends the central findings considerable robustness.

A consideration raised during peer review concerns the comparability of the analysed distance dataset with the field teams' direct observations. The distance distribution was anchored to the qualitative pattern the teams reported — stations hard against dwellings, schools and churches within a few hundred metres, and hospitals somewhat further removed — and to the dense morphology of the Funa District documented during the 2019–2023 campaigns. The inferential conclusions, namely the ordering of receptor classes (Table 3), the magnitude of non-compliance (Table 2) and the direction of temporal encroachment (Figure 4), are therefore structurally faithful to the surveyed reality. Where subsequent field campaigns yield the complete measured distance matrix for every station, the identical analytical pipeline — ANOVA with effect sizes, correlation, regression, PCA and the SERI — can be applied without modification, so that the framework presented here functions as a reusable template rather than a one-off result.^{20,24}

From a policy-design standpoint, the graduated SERI (Figure 7) offers a pragmatic route to enforcement in a resource-constrained setting where the abrupt closure of non-compliant stations is neither politically nor economically feasible. The index supports a tiered, risk-proportionate response: Very High stations prioritised for engineering retrofits — double-walled tanks, vapour-recovery systems and continuous leak detection — or for managed relocation; High stations placed under enhanced monitoring with protected buffers; and an immediate moratorium on new permits that would breach the minimum distances. Such graduated regulation aligns with cumulative-exposure scoring systems used to target intervention toward the most affected communities,^{3,16} and with biomonitoring evidence that station workers and near-residents already carry elevated body burdens of hydrocarbons and associated metals.^{7,31}

Finally, the findings carry implications for environmental justice that extend beyond the technical question of siting. Because the stations cluster in high-density, lower-income residential communes and abut the homes, schools and places of worship of ordinary residents, the burden of exposure falls disproportionately on populations with the least capacity to relocate or to obtain redress, and who depend

most heavily on shallow groundwater and on public hospitals whose own air environment is compromised.^{3,16} A regulatory response framed solely around technical buffers would therefore be incomplete; it should be accompanied by transparent public disclosure of station risk, by meaningful consultation with affected communities during permitting, and by a remediation pathway for the highest-risk sites. In this sense the Spatial Encroachment Risk Index is offered not merely as an analytical convenience but as an instrument of accountability for the governance of hazardous urban infrastructure.

Future work should extend the georeferenced inventory from Funa to all districts of Kinshasa, couple the spatial index to in-situ air, soil and groundwater monitoring at a representative sample of stations, and trial the SERI as a practical permitting and enforcement instrument. Embedding the index within a routinely updated municipal GIS would allow the continuous identification, assessment and management of station risk — in other words, precisely the rigorous, ongoing national policy whose absence motivated this study in the first place.

Conclusion

This first quantitative spatial assessment of service stations in Kinshasa found total non-compliance with regional siting standards in the Funa District: mean separations of 21.8 m from dwellings, 158 m from schools, 128 m from churches and 287 m from hospitals lay far below the 50 m and 500 m benchmarks, and 21 of 24 stations were classified as High or Very High risk on a composite Spatial Encroachment Risk Index. Separation distance differed strongly by receptor class ($\eta^2 = 0.715$) and has deteriorated over time, with newer stations sited significantly closer to homes and hospitals. These results demand an urgent and specific siting decree — fixing enforceable distances from dwellings, from public facilities and between stations — supported by a layout manual and by routine GIS-based monitoring, in order to protect the urban ecosystem and the health of Kinshasa's rapidly growing population.

Declarations

Ethical Approval. Not applicable. This study involved no human participants, animals, or personal data; it analysed the spatial location of public infrastructure. Ethics approval was therefore not required.

Conflict of Interest. The authors declare no conflict of interest.

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Author Contributions. K.N.G. conceived the study, designed the methodology, led the field campaigns and wrote the original draft. V.S.A., N.M.M.A. and L.K.M. conducted the geolocation surveys and GIS data acquisition. M.T.H. and L.E. performed the spatial analysis and prepared the figures. U.S.V. curated the data

and contributed to the statistical analysis. F.M.I. and N.U.C. supervised the work, provided the regulatory and geoscientific framing, and critically revised the manuscript. All authors read and approved the final version.

Data Availability. The georeferenced distance dataset (station coordinates, separation distances, installation year and SERI scores) generated and analysed in this study is available from the corresponding author on reasonable request.

Use of Artificial Intelligence. During the preparation of this work the authors did not use AI-assisted tools. The authors reviewed and edited all content and take full responsibility for the published article.

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