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City-wide space-time patterns of environmental noise pollution in Kigali, Rwanda

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Abstract

Background: As cities in Sub-Saharan Africa (SSA) become more crowded, noise pollution is also emerging as an important environmental concern, after air pollution. Yet, unlike air pollution, which is enjoying relatively more public attention, there is limited measurement data and policy efforts on environmental noise pollution.

Objective: We followed a recent city-wide measurement approach used in Accra (Ghana) and characterized environmental noise patterns in Kigali, a contrasting city with very different topography and regulatory system than Accra to inform urban policy.

Methods: We established 10 'fixed' (yearlong) and 120 'rotating' (weeklong) monitoring sites to capture both the temporal and spatial patterns in Kigali's sound environment. The measurement occurred between November 2022 and December 2023, and samples were collected at 1-minute interval, resulting in 5,155,014 (3,580 site-days) and 1,190,620 (827 site-days) site-minutes of valid data from the fixed and rotating sites, respectively. The 130 monitoring sites covered a variety of geographic and land-use factors across diverse neighborhoods and sources. We computed several noise metrics, including 1-hour ($LAeq_{1hr}$), daily ($LAeq_{24hr}$), day-time (L_{day}), and night-time (L_{night}).

Results: Daily noise ($LAeq_{24hr}$) levels across the city ranged between 38-85 dBA. Commercial, business, and industrial (CBI) and high-density residential (HD) communities experienced the highest noise levels, with some sites constantly above 70 dBA at day and 65 dBA at night. About 63% of our observed day-time values (up to ~72% in some areas) exceeded the Rwandan daytime standard (55 dBA) for residential areas, whereas 69% of the observed night-time values (up to 80% in some areas) exceeded the corresponding nighttime standard (45 dBA). In Nyarugenge, the most urbanized district, as much as 75% of our site-days data exceeded daytime standard. However diurnal patterns throughout the city were similar, rising from ~5am, peaking at about 8am and plateauing until 6pm before falling to their lowest at midnight. Overall, noise levels in the city did not vary much by day of the week, weekdays vs weekend, or dry vs wet seasons.

Conclusion: Environmental noise in Kigali often exceeded both Rwandan standards and international guidelines, with residents in the city center district, CBI and HD areas at risk of higher exposure, and hence higher risk of adverse effects. Detailed assessment of the sources, at-risk population, and associated health effects may inform Rwandan's environmental policy efforts and city initiatives in the face of the ongoing urban growth and densification.

1. Introduction

As socioeconomic opportunities continue to attract people to cities worldwide, urban dwellers are faced with the dangers posed by environmental hazards, including air and noise pollution[1–5]. Much like air pollution, urban environmental noise exposure has been shown to impact physical health and mental well-being[6–11]. Epidemiological studies, mostly investigating long-term population exposures to transportation noise in Europe, have shown robust associations with annoyance, sleep disturbance[12–15], and cardiometabolic health outcomes and risk factors[16–19]. However, there is limited epidemiologic studies in many places outside of Europe due to lack of high-resolution and city-scale exposure data [20–25]. As cities in developing countries become more crowded, noise pollution is also emerging as an important environmental concern, after air pollution [26–30] .

Presently, sub-Saharan Africa (SSA) has the world's fastest growing, youngest population, and the highest urban growth rate. Consequently, noise pollution is increasingly becoming a public health risk in growing cities [31–33]. While emerging measurement data have resulted in increasing resource mobilization and public campaigns to combat rising air pollution levels in SSA cities, similar efforts to manage urban soundscapes are limited. One key reason for this lack of public and policy engagement on noise pollution in the region is the scarcity of measurement data. The few measurement studies that exist have shown elevated noise levels that exceed international and national guidelines [32–36]. These studies have identified some urban sources that are similar to those in developed country cities (e.g. road traffic and aircraft) and others that are unique to SSA (e.g. loud music from informal businesses and religious activities in residential areas) [34,37–41]. With such diversity of sources in fast-sprawling SSA cities amid weak regulatory framework, city-wide measurements are critical for understanding the magnitude and spatial patterns of noise pollution and identifying at-risk communities and populations to inform policy interventions [32,41–45].

Considering the general lack of data in SSA, we developed and implemented in Accra (Ghana) a consistent and transferable protocol for generating rich environmental health data in urban SSA context, as part of the 'Pathways to Equitable Health Cities' project [45]. In Kigali, we implemented the Accra protocol to understand environmental noise patterns in a contrasting city with very different topography and regulatory system than Accra to inform policy as the city continues to expand and densify. Kigali, the capital of Rwanda and central hub for technology, is one of the few SSA cities with major government efforts to regulate noise and air pollution. These policy efforts include curfews, car-free days and zones, and a set time for closing non-essential services at night, all of which may help reduce noise pollution. Yet, no prior city-wide noise assessment exists for Kigali, which can provide broad baseline data on the patterns and neighborhoods at risk, and allow for the evaluation of the effectiveness of these policies. Here, we provide the first city-wide data on environmental noise in Kigali city.

2. Materials and Methods

2.1 Ethical Consideration

The study was approved by the Rwanda Environment Management Authority (REMA). The African Institute for Mathematical Sciences Research and Innovation Centre (AIMS-RIC) managed the field campaign. The original study protocols (implemented in Ghana) were approved by the Imperial College London and the University of Massachusetts Amherst.

2.2 Study area

The Kigali city spans an area of 730 Km^2 with ~1.75 million residents assembled in three administrative districts: Gasabo, Kicukiro and Nyarugenge [46]. Gasabo comprises primarily of agriculture land (background) and scattered mixed land use (areas with residential, commercial, and industrial activities), whereas Kicukiro is predominantly low- and medium-density residential communities. In contrast, Nyarugenge is the center and commercial hub of Kigali, and is characterized by dense commercial activities and heavy traffic. Kigali's population is growing at an annual rate of 4.4% since 2012, nearly twice the national average of 2.3% [46], resulting in substantial socioeconomic, demographic, and land use changes [47,48]. The built-up (more developed) areas increased from 48.6 Km² in 2003 to 238.1 Km² in 2023 [49]. The city's topography is characterized by hills, valleys, and ridges, with peaks reaching up to > 2,000 m above sea level (Fig.1). There are two rainy seasons in a year (March-May, and September-December), with dry season in June-August. As part of its green city and healthy initiatives, Kigali has instituted car-free days on the first and third Sundays of the month, where some roads are closed to vehicular traffic between 7am-10am to allow open walking and cycling, and routine vehicle emission inspections [50]. There are also car-free zones with pedestrian and bicycle lanes to promote non-motorized transport.

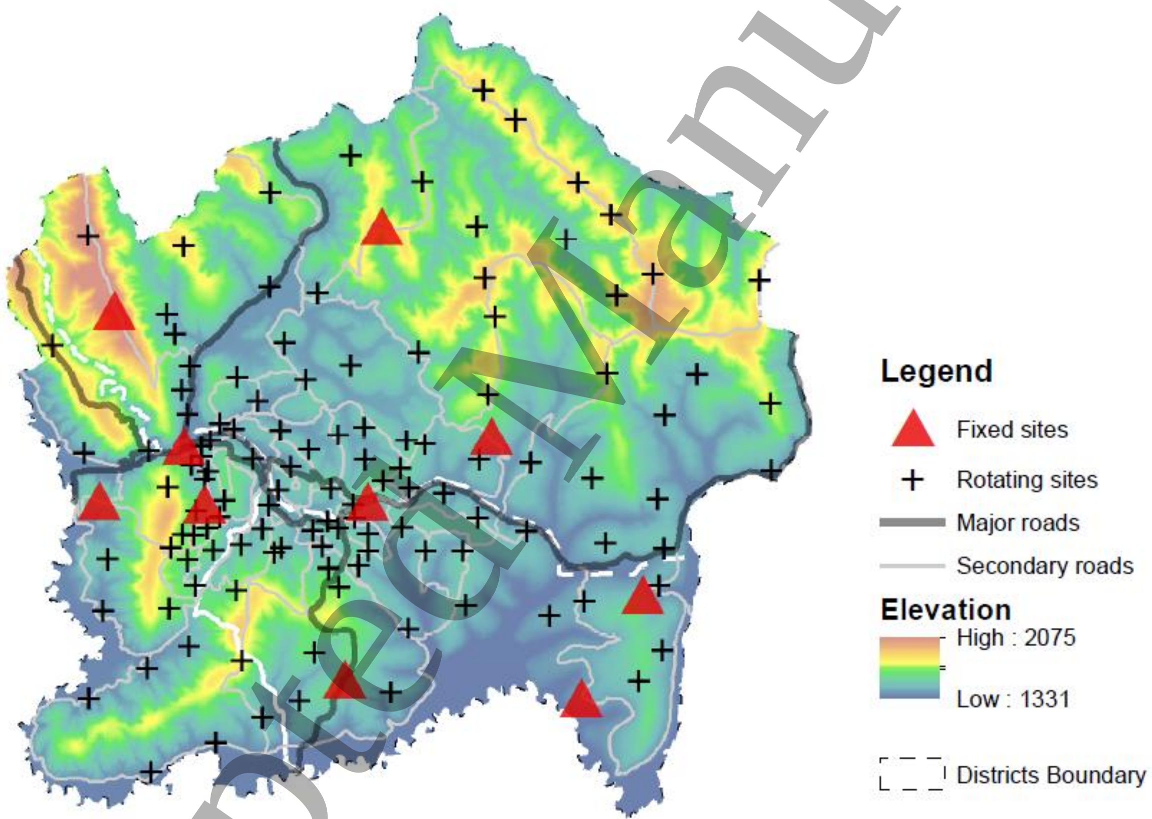

Figure 1: Map of Kigali city, showing elevation and monitoring sites. Fixed (yearlong) sites (n=10) are represented by red triangles and rotating (weeklong) sites (n=120) by black crosses. Elevation data (in meters) was sourced from open repositories and road networks were acquired from OpenStreetMap. See Figure S1 for the boundaries of the three administrative districts: Gasabo, Kicukiro and Nyarugenge.

2.3 Study design and site selection

Our study design followed the measurement approach used previously in Accra, Ghana [45]. In Kigali, we established 10 'fixed' (run continuously for a year; yearlong) and 120 'rotating' (run continlusly for a week; weeklong) monitoring sites to capture both the temporal and spatial patterns in the city's sound environment (Fig. 1). The field measurements occurred between November 2022 and December 2023. The monitoring sites were selected based on land use and geographic factors, aiming to capture noise levels across diverse neighborhoods and areas of varied noise sources (Fig. 2). Detailed site-specific information was documented using standardized log forms. Each site was then classified as one of four land use categories as defined by Kigali's City government's 2020 Master Plan: commercial, business, and industrial (CBI, n=19 [4 fixed and 15 rotating]); high-density residential (HD, n=28 [1 fixed and 27 rotating]); medium/low- density residential (LD, n=49 [2 fixed and 47 rotating]); or background/peri-urban (BG, n=34 [3 fixed and 31 rotating]) [51]. CBI areas cover places with commercial, business and industrial activities and along major roads with higher potential for noise. HD represents neighborhoods with dense and lower-income populations, narrow roads with substantial traffic with chances of noise from mix of traffic and human activities, whereas LD are communities with sparse to moderate concentration of dwellings and populations with higher incomes, wider roads and lower traffic. Compared to other land use types, BG areas include places with high green or open space and minimal traffic influence.

2.4 Sound level measurement

We captured maximum (L-Max dBA), equivalent continuous (LEQ dBA), and minimum (L-Min dBA) environmental sound levels using a Noise Sentry sound level meter (SLM) (https://convergenceinstruments.com/) with a dust-protected type I MEMS microphone [45,52]. The sensors were mounted on a wind and rain protective box on metal poles at ~4 m above ground and ~ 2 m away from any direct and surrounding noise sources and facades (Fig. 2). The data were recorded at one-minute intervals [53]. The Noise Sentry SLM sensors were validated against a Type I industry-standard instrument (DUO 01dB), and showed very high agreement with the mean and median second-by-second differences of −0.42 and −0.38 dBA, respectively[43,45]. During our monitoring campaign, the sensors were first collocated and tested in the lab and found high between- and within-sensor consistency. In the field, we collected duplicate samples at 33% (1 in 3) of the rotating sites (Figure S6). The absolute median and mean minute-by-minute difference between the duplicate and main samples were 0.89 (-0.02) and 1.3 (0.03) dBA, respectively.

Figure 2: Examples of the measurement setup, equipment, and sites.

2.5 Data management and noise metrics

We inspected the data for implausible readings and removed 0.32% minute-by-minute data points that were unrealistically low (<20 dBA); none were unrealistically high (>120 dBA) [54,55]. Our final analysis included 5,155,014 (3,580 site-days) and 1,190,620 (827 site-days) site-minutes of data from the fixed and rotating sites, respectively. For each site, we computed 1-hour ($LAeq_{1hr}$), daily ($LAeq_{24hr}$), day-time (L_{day}), and night-time (L_{night}) equivalent continuous noise levels, along with day-time and night-time intermittency ratios (IR_{day}, IR_{night}) (%) [43,56]. The intermittency ratio (IR) is defined as the ratio of event-based sound energy to the total sound energy during a given measurement period, and expressed as percentage [16,57,58]; where 0% indicates no distinct noise events above the background, and 100% indicates all noise energy comes from individual events [16,32]. In this study and similar to past studies [43,56], we used a threshold of +3 dBA above the $L_{eq,T,tot}$ (offset C = 3 dBA). Following the Rwandan acoustic standards, we defined day-time as 06:00 – 20:59 and night-time as 21:00 – 05:59 [59].

Both sound level and event metrics were summarized using the median and interquartile range (IQR) as a measure of central tendency and spread/variation as the measured data were not normally distributed. Using data from the fixed sites, we examined temporal patterns in the noise metrics across various time spans, including diurnal, days of the week, weekdays vs weekends, and rainy vs dry season. Spatial patterns were evaluated across the four land use categories (CBI, HD, LD, and BG) using data from both the fixed and rotating sites. We also compared noise levels across the three administrative districts. Further, we examined the percent of sites/data that surpassed the Rwandan standard for residential areas [59] and the World Health Organization (WHO) 2018 European Environmental Noise guidelines [60,61]. Data analysis and visualization were performed using R (R version 4.5.0).

3. Results

3.1 Spatial patterns in noise level and event metrics

The median (IQR) daily ($LAeq_{24hr}$) across all 120 rotating (weeklong) sites was 54.7 (IQR: 50.5, 58.7) dBA, with CBI areas ~5 dBA louder (i.e. ~ three times more intense) than BG areas (Table 1). Day-time (L_{day}) median noise levels ranged from 54.7 (IQR: 51.4, 59.1) dBA and 54.6 (IQR: 51.4, 58.2) dBA at BG and LD areas, to 57.2 (IQR: 54.3, 61.9) dBA at HD, and 59.3 (IQR: 56.0, 65.5) dBA at CBI areas. There was about 8 dBA drop in the overall noise levels between day-time and night-time (56 vs 48 dBA), which is ~6-fold reduction in sound energy and nearly half the perceived loudness. The highest night-time (L_{night}) median noise levels of 53.3 (IQR: 50.8, 59.8) dBA occurred at CBI areas, and they were about the same as the lowest day-time levels at LD and BG areas. Within land-use categories, BG sites experienced the highest day- and night-time variability (~10 dBA), compared to ~6.0 dBA across the other land use categories. BG and LD residential areas also had the highest median intermittency ratios in both the day and at night (> 50%), whereas CBI areas were below 50%. In general, land use areas with higher sound levels had lower intermittency ratios (Table 1). The yearlong data from the individual fixed sites also followed the same land use pattern, with the highest median daily ($LAeq_{24hr}$) level of ~70 dBA observed at a traffic dominant site whereas the lowest levels were recorded at peri-urban sites (Table S1). Consequently, IRs at traffic and CBI sites were substantially lower than IRs at other land use sites (Table S1).

Figure 3 shows the spatial distribution of the measured noise (L_{day}, L_{night}, IR_{day}, IR_{day}) levels across the entire city. In general, measurement sites in the more remote areas with scattered settlements had the lowest noise levels in comparison to densely populated and central areas closer to residences, major roads, and business activities. The median day-time (L_{day}) at measurement sites along major roads ranged 54.5-63.2 dBA compared to 52.4-57.8 dBA in residential areas. A similar pattern was observed at night-time between traffic and residential areas, except that the levels were about ~6 dBA lower at night.

Across the three administrative districts (Fig. S1), both day-time (L_{day}) and night-time (L_{night}) noise levels were often above the national standards for residential areas (55 dBA for day and 45 dBA for night), particularly in the busiest Nyarugenge district where 75% of the daytime values exceeded the day-time limit, compared to ~50% in the other two districts (Fig. 4 and Table 2). While over 60% of the data in all three districts exceeded the night-time limit, Gasabo district was relatively quieter than both Kicukiro and Nyarugenge, which was the loudest even at night. Regardless of the district, there were also strong within-district differences, which were driven by land use activities.

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Table 1: Median (IQR) noise level and event metrics across land use categories

Sites and site-types (n)	Noise metric (dBA)			Event metric (%)	
	$LAeq_{24hr}$	L_{day}	L_{night}	IR_{day}	IR_{night}
All rotating sites (120; 826 site-days)	**54.7 (50.5, 58.7)**	**56.1 (52.1, 59.8)**	**48.2 (43.8, 53.6)**	**46.0 (30.5, 60.8)**	**55.4 (37.8, 70.9)**
Background/Peri-Urban (BG): (31)	52.9 (49.6, 57.6)	54.7 (51.4, 59.1)	44.5 (41.7, 48.8)	51.1 (40.0, 62.2)	61.5 (43.5, 74.6)
Medium/low-density residential (LD): (47)	53.4 (50.1, 57.2)	54.6 (51.4, 58.2)	48.0 (43.4, 52.4)	52.1 (35.5, 63.6)	59.0 (40.3, 75.1)
High-density residential (HD): (27)	55.7 (52.6, 60.3)	57.2 (54.3, 61.9)	50.2 (45.3, 54.8)	37.8 (25.0, 53.8)	49.4 (33.2, 61.3)
Commercial/Business/Industrial (CBI): (15)	57.8 (54.4, 64.3)	59.3 (56.0, 65.5)	53.3 (50.8, 59.8)	34.2 (22.8, 44.8)	49.3 (34.1, 57.7)
All fixed sites (10; 3584 site-days)	**56.8 (51.7, 66.6)**	**58.1 (53.1, 68.2)**	**49.2 (44.0, 57.3)**	**46.8 (28.8, 65.2)**	**51.6 (39.7, 66.6)**
Background/Peri-Urban (BG): (3)	51.2 (47.1, 54.2)	52.7 (48.5, 55.7)	42.9 (38.4, 45.5)	59.5 (50.6, 70.8)	63.0 (47.2, 75.6)
Medium/low-density residential (LD): (2)	56.3 (53.3, 58.5)	57.9 (54.8, 60.1)	48.3 (47.1, 50.1)	52.6 (40.9, 70.8)	63.4 (53.1, 76.6)
High-density residential (HD): (1)	57.1 (56.2, 58.3)	58.1 (57.2, 59.3)	53.8 (53.0, 54.7)	31.9 (24.6, 42.3)	46.6 (41.3, 52.4)
Commercial/Business/Industrial (CBI): (4)	67.7 (61.9, 69.4)	69.4 (63.6, 70.8)	60.0 (54.0, 65.5)	28.2 (15.5, 49.1)	42.6 (28.5, 51.8)

$LAeq_{24hr}$: A-weighted equivalent continuous 24-h noise level; L_{day} and L_{night}: A-weighted equivalent continuous noise level in the day and night-time; IR_{day} and IR_{night}: Day- and night-time intermittency ratios (%). Commercial/Business/Industrial (CBI) are places with commercial, business and industrial activities and along major roads; high-density residential (HD) represent neighborhoods with dense populations, narrow roads, and high biomass use; medium-/low density residential (LD) are neighborhoods with sparse to moderate concentration of dwellings and populations with wide roads and low biomass use; and background/peri-urban (BG) areas are places with high green or open space and minimal traffic influence. See Table S3 for detailed number of samples by site-days and site-hours for each noise metric/event and land use type classifications.

Table 2: Population characteristics and noise levels across districts.

District	Gasabo	Kicukiro	Nyarugenge
Percent of Kigali population (%)	50.4	28.2	21.4
Population density (people/km^2)	2,056	2,944	2,830
Noise pollution (IQR)			
Day-time (L_{day})	54.9 (51.5, 59.0)	55.4 (52.2, 58.9)	58.2 (54.9, 63.5)
Night-time (L_{night})	47.0 (43.3, 52.2)	48.8 (44.6, 53.4)	51.3 (44.1, 56.1)
Daily ($LAeq_{24hr}$)	53.4 (50.0, 57.1)	54.3 (50.8, 57.8)	56.9 (53.4, 61.8)
Event metrics			
IR_{day}	44.8 (32.3, 59.6)	50.0 (31.9, 61.8)	44.7 (28.7, 61.7)
IR_{night}	55.4 (35.3, 71.4)	58.3 (38.9, 74.6)	53.0 (38.9, 64.5)
IR_{daily}	1.91 (0.40, 5.64)	2.74 (0.77, 8.60)	1.39 (0.19, 4.53)

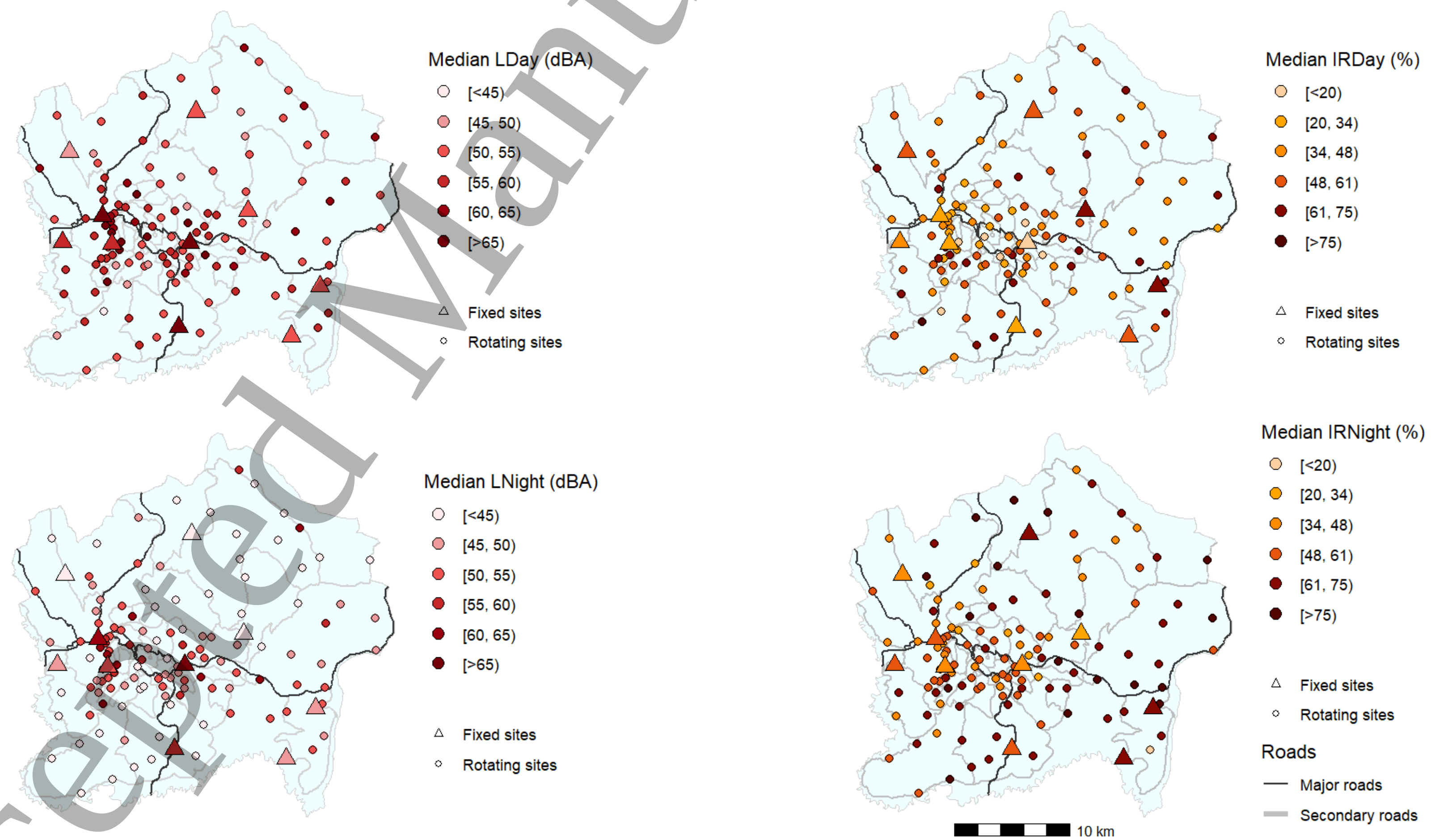

Figure 3: Spatial distribution of day-time (L_{day}) and night-time (L_{night}) median noise levels, along with the intermittency ratio during day-time (IR_{day}) and night-time (IR_{night}) for both rotating and fixed monitoring stations. Triangle markers represent yearlong fixed sites and circle markers indicate rotating sites.

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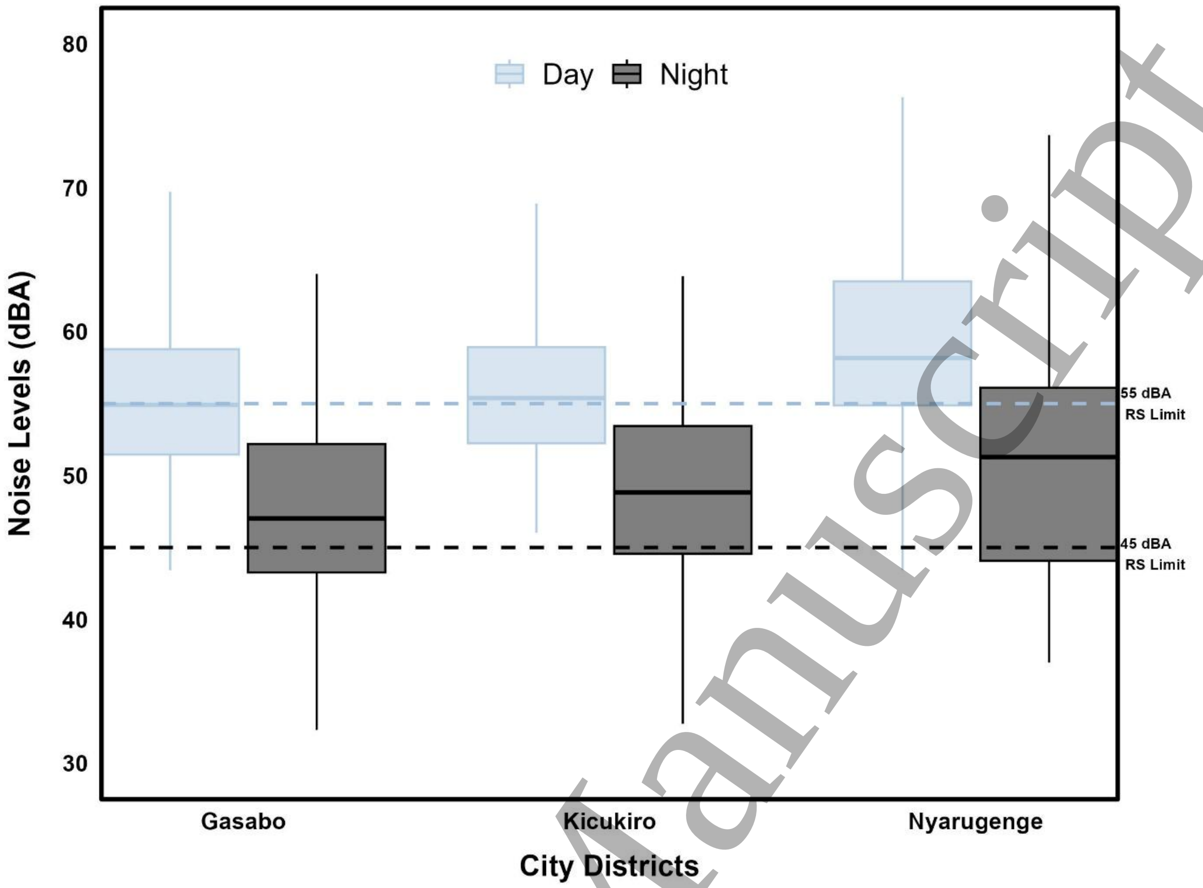

Figure 4: Box plots displaying the distribution of day-time (L_{day}) and night-time (L_{night}) noise levels (for rotating data) by districts of Gasabo (n=57), Kicukiro (n=32), and Nyarugenge (n=31). The dashed lines represent the Rwandan national noise standards of 55 dBA during the day and 45 dBA at night for residential areas.

3.2 Temporal patterns in noise level and event metrics

All sites and site-types exhibited similar diurnal patterns in noise level across time of day (Fig. 5). Median hourly noise ($LAeq_{1hr}$) levels rose from around 5am, peaked at about 8am and plateau until 6pm when they began to fall to their lowest between midnight to 4am (Fig. 5 and Fig. S2). Between 6am-8pm, the median hourly ($LAeq_{1hr}$) levels at CBI and HD areas exceeded the Rwandan day-time limit of 55 dBA for residential areas. This pattern existed also at the fixed sites when the data was aggregated across the full year, particularly sites dominated by traffic and commercial activities. Overall, ~44% of the hourly ($LAeq_{1hr}$) data at day-time hours exceeded the 55 dBA threshold for residential areas, whereas 54.3% of night-time data exceeded the 45 dBA limit.

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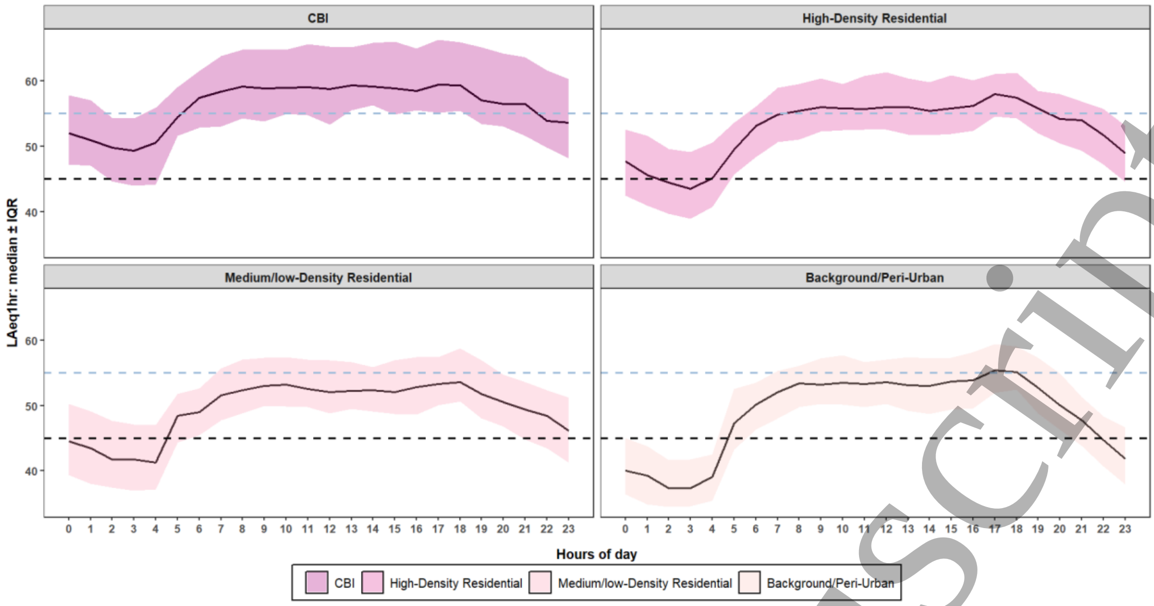

Figure 5: Diurnal variation of hourly noise ($LAeq_{1hr}$) levels across time of day and site types. Trend lines show hourly median noise levels, with shaded areas representing the 25% to 75% percentiles. The horizontal dashed lines are the 45 and 55 dBA Rwanda day- and night-time limit for residential areas respectively.

For day versus night, the median day-time noise levels (L_{day}) at CBI sites was 58.8 dBA compared to 52.4 dBA at night. They were 55.8 vs 48.0 dBA at HD areas, 52.4 vs 45.4 dBA at LD neighborhoods, and 53.3 vs 41.5 dBA at BG sites. During the day, ~72% of the data at CBI and ~57 % at HD exceeded the national limit, compared to only ~36% in BG sites. At night, 82% of the CBI data exceeded the national night-time limit of 45 dBA, followed by 66% at HD, 52% at LD, and 34% at BG. In general, CBI consistently showed the highest exceedance rates for both day and night limits whereas BG had the lowest exceedance rates. Although car-free Sundays only occur on certain roads (same road) on the first and third Sunday of the month and for a limited time (07-10:00) only, we observed ~3 dBA reductions in the hourly ($LAeq_{1hr}$) levels in HD areas, representing a 50% reduction in the sound energy. We found no clear impact of the car-free policy within other land use groups.

Over the one-year measurement period, daily ($LAeq_{24hr}$) noise levels ranged from 38.1 dBA at a background site to 84.6 dBA at a high-density residential site. By days of the week, the median noise levels during weekdays and weekends were nearly identical for each land use type (Fig. 6 and Fig. S3). It was 56.7 vs 57.0 dBA at CBI sites and 49.6 vs 50.5 dBA at medium/low-density residential and background/peri-urban sites. By season, the range of median daily ($LAeq_{24hr}$) values (low vs high) were similar for dry (44 vs 70 dBA) and rainy (46 vs 70) dBA seasons. However, LD and BG fixed sites (e.g. RSH and JL) demonstrated noticeable month-to-month fluctuations. Throughout the year across the individual ten fixed sites, daily ($LAeq_{24hr}$) noise levels at sites dominated by traffic (AIMS and NBG) consistently averaged around 70 dBA (Fig. 7, Fig. S7). Five of the 10 sites located in CBI and HD areas had daily ($LAeq_{24hr}$) levels above the day-time limit, while LD and BG sites mostly recorded levels above nighttime limits and sometimes above daytime limits (Fig. 7).

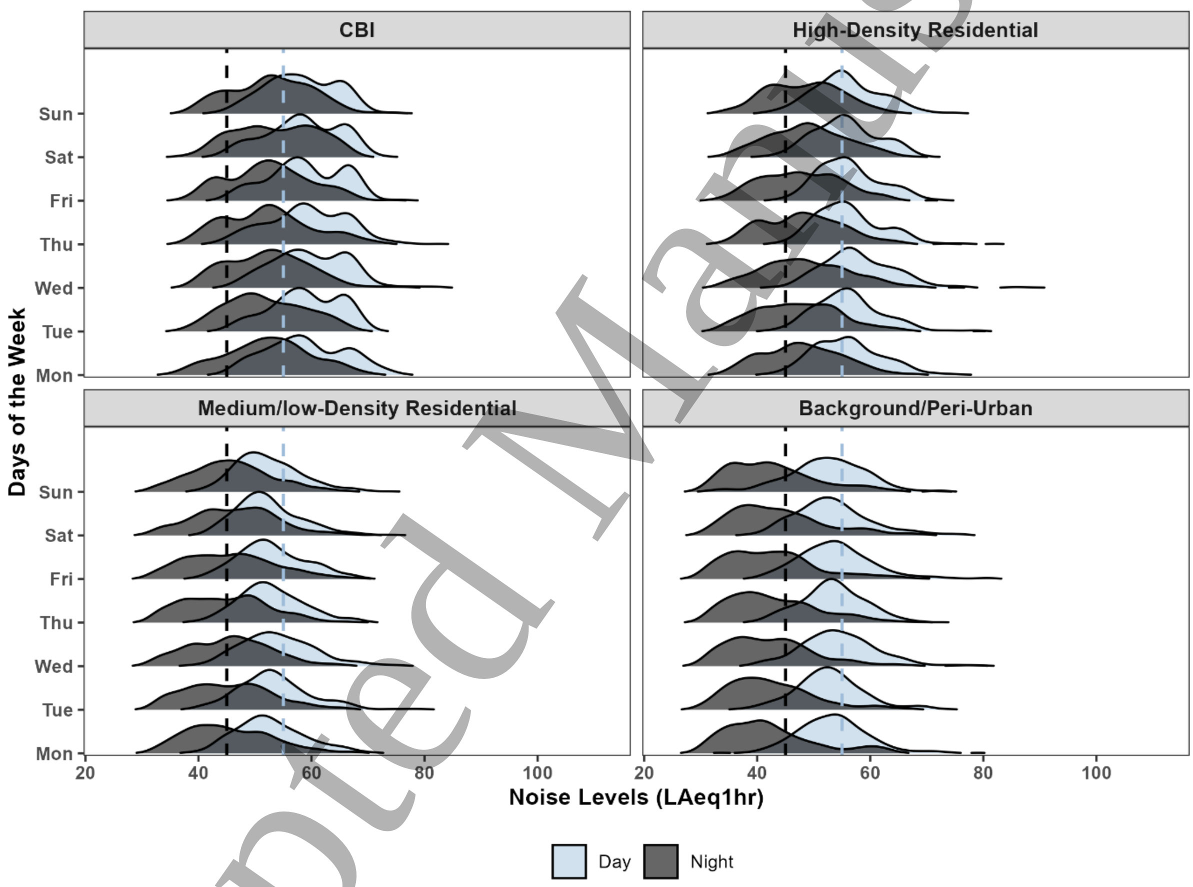

Figure 6: **Distribution of day- (L_{day}) and night (L_{night}) -time noise levels by site types.** Day-time is defined as 06:00-20:59 and night-time as 21:00-05:59 according to Rwanda Standard. The vertical dashed lines represent night-time (45 dBA) and day-time (55 dBA) national permissible limit for residential areas, respectively.

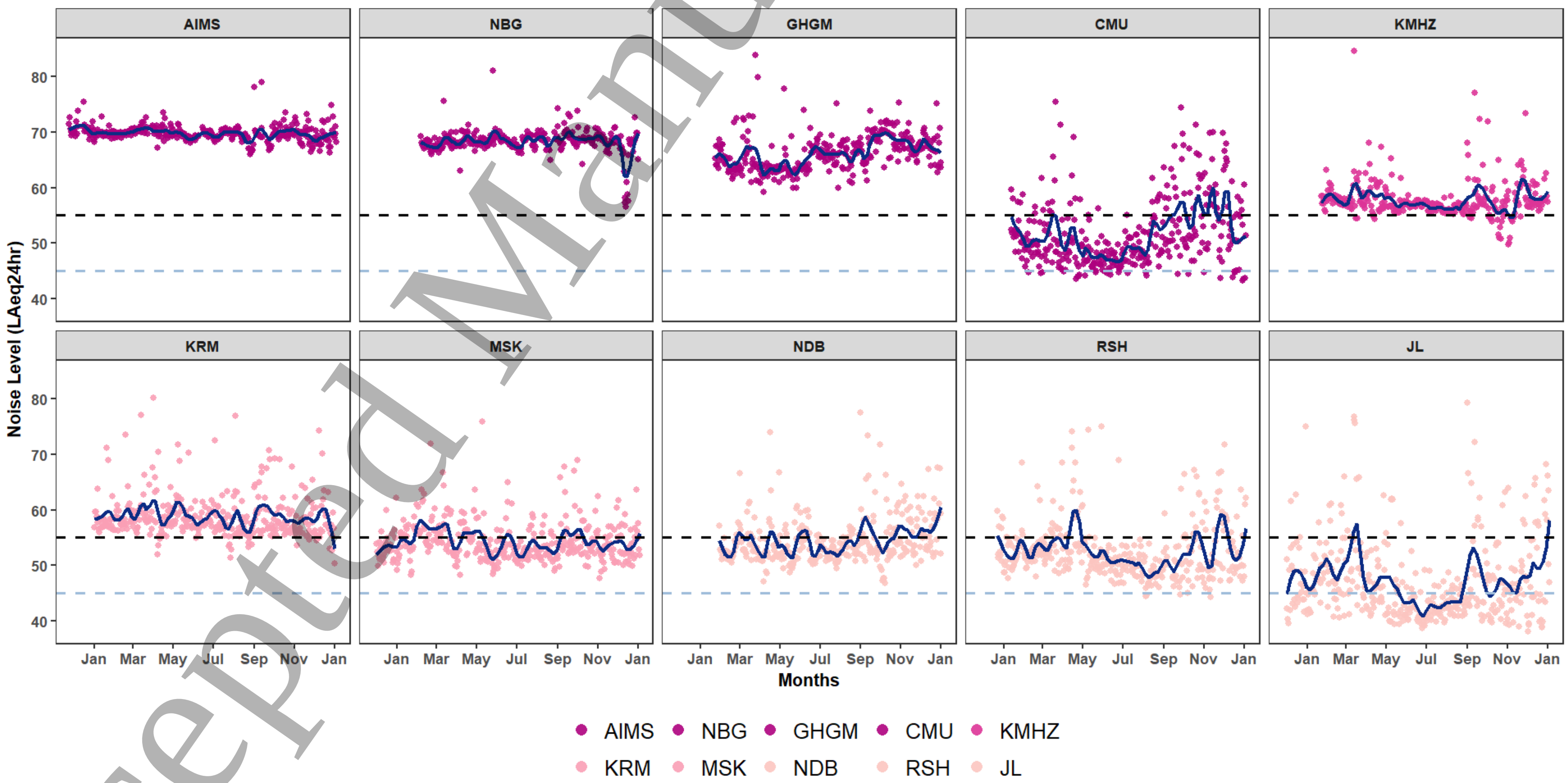

Figure 7: Timeseries of daily ($LAeq_{24hr}$) noise levels across the full measurement year at the 10 fixed sites. The figure presents site-specific differences, temporal trends and seasonal variations. Commercial, business, industrial (AIMS, NBG, GHGM, CMU); high-density residential (KMHZ); medium/low-density residential (KRM, MSK) and background/peri-urban (NDB, RSH, JL). The two dashed lines represent the day-time (55 dBA) and night-time (45 dBA) national permissible limits for residential areas.

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4. Discussion

Unlike most fast-growing cities in SSA, Kigali has strong policy and regulatory framework around transport and commercial and residential activities with the goal of curbing environmental exposures [59,62]. The city enforces routine vehicle emission inspections and residential night-time curfews on certain activities to reduce noise and air pollution accordingly. Its green city and healthy initiatives include car-free zones and days to promote non-motorized transport and reduce pollution. Yet, it is unknown what the levels are throughout the city and how they vary across various communities and over time. Such information is relevant for assessing the effectiveness of these policy interventions over time and informing future city planning goals. Following a large-scale citywide year-long measurement campaign, we found that environmental noise levels in Kigali were strongly patterned by land-use features, with the highest levels at traffic-dominant CBI and HD residential communities. Across the city, daytime and nighttime noise levels often exceeded the Rwandan national standards and international guidelines for residential areas, particularly in Nyarugenge district, CBI, and HD neighborhoods. We also found a large difference between day-time and night-time levels, regardless of the land-use type. However, the highest night-time levels at CBI areas were about the same as the lowest day-time levels recorded at LD and BG areas, which also experienced the largest day- and night-time variability. Further, we found that areas with the highest sound levels had the lowest IRs, suggesting consistent continuous high background noises at these sites. Overall, we observed no significant differences across days of the week, between weekdays vs weekend, or dry vs wet seasons.

Our study was modelled after a previous one conducted in Accra, Ghana, with the aim of generating rich environmental health data in an urban SSA context [45]. But unlike Accra, Kigali is smaller in area, population, and traffic density; has a topography consisting of steep hills and valleys with a greener landscape; and with stronger environmental regulation and sustainability goals [63,64]. Consequently, environmental noise levels recorded in Accra were slightly higher than in Kigali [32,43]. Despite the above key differences between the two cities, our findings of the spatial and temporal patterns are consistent with the Accra data. Like Accra, we found higher noise levels, as expected, in areas with CBI activities and in densely populated residential neighborhoods, exceeding local standard and international guidelines [37,38,43,65–67]. Residents living in the more urbanized and densely populated districts of Kicukiro and Nyarugenge, constituting ~50% of Kigali's population, are at risk of higher exposure, and hence higher risk of associated adverse effects[68].

Just as Accra, we found no seasonal and weekdays variations in the Kigali's soundscape, except for diurnal (day vs night) differences that were in themselves also impacted by land use factors. Kigali also experienced much larger day-/night-time differences, which could be attributed to its night-time residential noise control policies and/or lesser night-time economic/social activities than seen in Accra. In Kigali, we found that BG and LD residential areas in general had higher intermittency ratios (event-based sound energy, >50%) both in the day and at night compared with HD and CBI areas. This is likely because the average baseline noise levels in these areas are lower, and therefore, intermittent and distinct noise events are more detectable. The Accra study [43] found slightly lower intermittency ratios than what we recorded in Kigali.

Studies of relatively smaller scope and duration in other SSA cities (e.g. Johannesburg, South Africa; Ibadan, Nigeria; Nairobi, Kenya; and Iringa, Tanzania) also found the same spatial patterns of environmental pollution across land use factors [31,65,69–73], and the levels far exceeded international guidelines. Studies from major cities in North America (e.g., Atlanta, Los Angeles, and New York) [74], Europe (e.g., Paris, London and Amsterdam) [75] and Asia (e.g., Doha, Guangzhou and Seoul) [76–78] have also documented variations in environmental noise levels with respect to land use patterns. In American and European cities, elevated noise levels are driven primarily by transportation (road, rail, and aircraft) and industrial activities. In Kigali, noise levels are equally high in traffic congested areas and commercial districts in addition to densely populated residential areas [79–81]. Generally, the levels recorded in Western cities due to transportation are higher than observed in Kigali, which is likely due to Kigali's lower traffic volume and strong speed control policy (speed limits are tightly controlled/enforced with speed cameras in Kigali). However, the share of Kigali's population that live in areas exceeding regulatory standards and health guidelines is likely higher than in Western cities.

The WHO has developed a set of guidelines over the years to limit public health impacts of exposure to noise pollution from environmental sources, with the most recent update in 2018 [61]. A number of SSA countries, including Rwanda, Ghana, Tanzania, and South Africa, have also established national limits to safeguard public health, but large-scale monitoring efforts to support compliance and health studies are generally lacking [21,31,43,82]. Where they exist, as has been shown in Accra (and now Kigali), several local communities are not meeting these requirements. Between 36-72% (daytime) and 34-82% (nighttime) of our observed noise data across different land use categories in Kigali city exceeded Rwanda's standard for residential areas (55 dBA for daytime) and (45 dBA for nighttime). Those living in densely populated neighborhoods and commercial districts are at higher risks of exposure [83] and potential adverse impacts like annoyance and disturbances in sleep quality and quantity [80,84,85].

We observed systematic diurnal patterns in noise levels across the city, rising early morning and peaking at and plateauing between 8am-6pm. This is consistent with patterns of rush hours in a typical 9am-5pm working hours and peaks with traffic and commercial activities. Public transportation during this period is characterized by traffic congestion from combination of diesel buses, motorcycle taxis, and taxicabs. Thus, the substantially consistent higher day-time noise in CBI and high-density residential areas may be due to traffic movements, loudspeakers used for advertisement, and sounds from local bars, exposing residents to levels of health concern. However, Rwanda's policy of restricted loud activities and noise emissions during nighttime (e.g. closure of clubs/bars by 1am on weekdays and 2 am on weekends) may be contributing to the substantially lower nighttime noise across board, although many communities still experience nighttime noise levels above the local standard. To promote the wellbeing of residents, the city of Kigali implemented noise pollution related mechanisms such as quiet and free zones, time-based noise restrictions, and urban planning regulations [86]. There is an indication that Kigali's car-free hours on the first and third Sundays of the month may be reducing noise levels during that time, especially in densely populated residential areas, and needs to be expanded to achieve city-wide impact. Though the 3 dBA seems small and may even be barely noticeable to most people, it represents a 50% reduction in the sound energy reaching their ears, which can meaningfully reduce risks of hearing loss, annoyance, or stress-related health effects over longer periods of exposure. Thus, expanding these policies across board will benefit Kigali residents. Further, the observed higher intermittency ratio in relatively quieter LD and BG areas could indicate more irregular noise patterns, which likely adds to the effect of noise exposure on health[57].

Though consistent with Accra, our observed lack of seasonal and weekdays differences contrasts with most studies in North American and European cities that found higher noise on weekdays[87–90]. This could be explained by regional variations in traffic patterns, urban infrastructure, and daily patterns of social and economic activities. Rapidly growing SSA cities like Kigali and Accra may be experiencing a more balanced commercial and commuter traffic throughout the week than in North America and Europe, where weekday peaks reflect more structured work schedules and commuter traffic.

As the city forges towards its ambition of growing and densifying within its unique physical layout of varying topography and greenery, it must combine timely data, city planning, and regulation to meet the growth/densification ambition, and associated mobility needs, and yet minimize environmental impacts like noise. To ensure urban change enhances health, well-being and sustainability, solutions may well include an effective public transport system that connects the city but is less polluting. One such example could be aerial tram/cable-car systems, which can work well for Kigali's topography and reduce both traffic congestion and

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pollution. Cities like La Paz (Bolivia) [91,92], Mexico City (Mexico) [93], Medellin City (Colombia) [94], Portland (USA), and Toulouse (France) [95] have incorporated aerial tramways or cable cars into their public transportation system and have been shown to reduce environmental pollution. Further, including the use of hybrid and fully electric buses in the public transportation system can also reduce noise pollution, particularly when combined with speed control and paving of road surfaces with low-noise materials. This is timely as Rwanda looks to restrict the importation of old vehicles.

4.1 Strengths and limitations

We employed a unique study design that allowed us to capture in detail the space-time variations in sound levels across an entire city. A major strength of our study is its large-scale, citywide and year-long measurement campaign involving > 6.3 million site-minutes (4,407 site-days) of data, enabling an in-depth analysis of spatiotemporal variations in environmental noise across diverse land-use settings. By capturing data from a broader range of residential, commercial, and mixed-use locations, we provide valuable insights into how specific urban features and human activities influence noise pollution. These findings offer crucial evidence to guide effective policy interventions and urban planning aimed at mitigating noise and improving public health.

As a limitation, we did not capture audio to objectively assess contributions from specific sound sources (e.g., traffic, loudspeakers, and nightlife establishments). Consequently, we cannot quantify the relative contributions of different noise generators or confirm when and where certain sources dominate, though we have inferred potential source influence through land use patterns. Additionally, while the study spanned a year and covered multiple seasons, more in-depth assessments (e.g., holiday effects, or variations in socio-economic activities) at targeted locations could enrich our understanding of noise dynamics. Despite these constraints, this work lays a strong foundation for the ongoing efforts to characterize and address environmental noise pollution in Kigali and other fast-growing SSA cities.

SSA cities that are looking to implement similar study design must be aware of a few key logistical challenges during the data collection, including sensor placement and access to optimal locations that reflect the city's land use patterns. Also, quantifying the relative contributions from specific sources in SSA's complex urban environment using combination of sound meters and audio will be critical for targeted policy interventions. Further, involvement of relevant local and national government agencies in the study design and interpretation of the results will be important for policy uptake and use of the data.

5. Conclusion

Like many SSA growing cities, Kigali faces environmental challenges, including noise pollution, which poses health risks to its residents. Yet, like other cities, Kigali lacked consistent city-wide noise to support policy efforts. We demonstrated in Kigali the successful transfer of our Accra protocol, which was designed generate rich environmental health data in urban SSA context. Our data show that there are a lot of areas, including residential communities in Kigali that far exceed the noise standards set by Rwanda and the WHO guideline. The findings call for targeted policies to achieve quieter, and hence healthier, living environment for Kigali residents in the face of the ongoing urban expansion.

Author Contributions

Jean Remy Kubwimana: Conceptualization, data curation, formal analysis, visualization, methodology, writing-original draft, writing-review & edits. Sierra N. Clark: Conceptualization, data curation, formal analysis, methodology, and writing-review & edits. James Nimo: Data curation, writing-review & edits. Chantal Umutoni: Data curation, writing-review & edits. Pacifique Karekezi: Data curation, writing-review & edits. Barbara E. Mottey: Data curation, writing-review & edits. Claudette Nyinawumuntu: Data curation, writing-review & edits. Samson Niyizurugero: Data curation, writing-review & edits. Silas S. Mirau: Writing-review & edits and Supervision. Pie-Celestin Hakizimana: Site access, writing-review & edits. Isambi S.

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Mbalawata: Project administration, resources and writing-review & edits. Paterne Gahungu: Conceptualization, data curation, writing-review & edits and Supervision. Majid Ezzati: Conceptualization, writing-review & edits. Allison F. Hughes: Data curation, writing-review & edits. Raphael E. Arku: Conceptualization, formal analysis, methodology, project administration, resources, writing-review & edits and Supervision.

Data Availability

Data will be fully made publicly available upon completion of the analyses.

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Declaration of competing interests

The authors declare no competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

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Additional Information

Supplementary Information

References

1. Adza WK, Hursthouse AS, Miller J, Boakye D. Exploring links between road traffic noise , air quality and public health using DPSEAA conceptual framework : a review and perspective for a UK environmental health tracking system (EHTS). *Environ Dev Sustain*. 2024;26(3):5579-5605. doi:10.1007/s10668-023-02996-6
2. Münzel T, Hahad O, Sørensen M, et al. Environmental risk factors and cardiovascular diseases: a comprehensive expert review. *Cardiovasc Res*. 2022;118(14):2880-2902. doi:10.1093/cvr/cvab316
3. Behsoodi MM. A Comprehensive Review of Noise Pollution and its Impact on the Urban Kardan Journal of Engineering and A Comprehensive Review of Noise Pollution and its Impact on the Urban Environment. 2024;(April). doi:10.31841/KJET.2022.26
4. Vardoulakis S, Dear K, Wilkinson P. Challenges and Opportunities for Urban Environmental Health and Sustainability : the HEALTHY-POLIS initiative. 2016;15(Suppl 1):1-4. doi:10.1186/s12940-016-0096-1
5. Tang JH, Jian HL, Chan TC. The impact of co - exposure to air and noise pollution on the incidence of metabolic syndrome from a health checkup cohort. *Sci Rep*. Published online 2024:1-12. doi:10.1038/s41598-024-59576-5
6. Clark C, Crumpler C, Notley H. Evidence for environmental noise effects on health for the United Kingdom policy context: A systematic review of the effects of environmental noise on mental health, wellbeing, quality of life, cancer, dementia, birth, reproductive outcomes, and cognition. *Int J Environ Res Public Health*. 2020;17(2). doi:10.3390/ijerph17020393
7. Stansfeld SA. Noise effects on health in the context of air pollution exposure. *Int J Environ Res Public Health*. 2015;12(10):12735-12760. doi:10.3390/ijerph121012735
8. Chen X, Liu M, Zuo L, et al. Environmental noise exposure and health outcomes: an umbrella review of systematic reviews and meta-analysis. *Eur J Public Health*. 2023;33(4):725-731. doi:10.1093/eurpub/ckad044
9. Organization WH. Burden of disease from environmental noise: Quantification of healthy life years lost in Europe. *World Heal Organ*. Published online 2011:126.
10. Herrera C, Cabrera-Barona P. Impact of Perceptions of Air Pollution and Noise on Subjective Well-Being and Health. *Earth (Switzerland)*. 2022;3(3):825-838. doi:10.3390/earth3030047
11. Clark SN, Anenberg SC, Brauer M. Global Burden of Disease from Environmental Factors. *Annu Rev Public Health*. 2025;46(1):233-251. doi:10.1146/annurev-publhealth-071823-105338
12. Peris E, Fenech B. Associations and effect modification between transportation noise, self-reported response to noise and the wider determinants of health: A narrative synthesis of the literature. *Sci Total Environ*. 2020;748. doi:10.1016/J.SCITOTENV.2020.141040
13. Guski R, Schreckenberg D, Schuemer R. WHO environmental noise guidelines for the European region: A systematic review on environmental noise and annoyance. *Int J Environ Res Public Health*. 2017;14(12):1-39. doi:10.3390/ijerph14121539
14. Fenech B, Clark S, Rodgers G. An update to the WHO 2018 Environmental Noise Guidelines exposure response relationships for annoyance from road and railway noise. *Internoise 2022 - 51st Int Congr Expo Noise Control Eng*. Published online 2022. doi:10.3397/in_2022_0244
15. Smith MG, Cordoza M, Basner M. Environmental Noise and Effects on Sleep: An Update to the WHO Systematic Review and Meta-Analysis. *Environ Health Perspect*. 2022;130(7):1-23. doi:10.1289/EHP10197
16. Héritier H, Vienneau D, Foraster M, et al. Transportation noise exposure and cardiovascular mortality: a nationwide cohort study from Switzerland. *Eur J Epidemiol*. 2017;32(4):307-315. doi:10.1007/s10654-017-0234-2
17. Zaman M, Muslim M, Jehangir A. Environmental noise-induced cardiovascular, metabolic and mental health disorders: a brief review. *Environ Sci Pollut Res*. 2022;29(51):76485-76500. doi:10.1007/s11356-022-22351-y

18. Münzel T, Kröller-Schön S, Oelze M, et al. Adverse cardiovascular effects of traffic noise with a focus on nighttime noise and the new WHO noise guidelines. *Annu Rev Public Health*. 2019;41:309-328. doi:10.1146/annurev-publhealth-081519-062400
19. Münzel T, Sørensen M, Daiber A. Transportation noise pollution and cardiovascular disease. *Nat Rev Cardiol*. 2021;18(9):619-636. doi:10.1038/s41569-021-00532-5
20. Moroe N, Mabaso P. Quantifying traffic noise pollution levels: a cross-sectional survey in South Africa. *Sci Rep*. 2022;12(1):1-12. doi:10.1038/s41598-022-07145-z
21. Kalisa E, Irankunda E, Rugengamanzi E, Amani M. Noise levels associated with urban land use types in Kigali, Rwanda. *Heliyon*. 2022;8(9):e10653. doi:10.1016/j.heliyon.2022.e10653
22. Oguntunde PE, Okagbue HI, Oguntunde OA, Odetunmibi OO. A study of noise pollution measurements and possible effects on public health in ota metropolis, Nigeria. *Open Access Maced J Med Sci*. 2019;7(8):1391-1395. doi:10.3889/oamjms.2019.234
23. Hammer MS, Swinburn TK, Neitzel RL. Environmental noise pollution in the United States: Developing an effective public health response. *Environ Health Perspect*. 2014;122(2):115-119. doi:10.1289/ehp.1307272
24. Pradeep L, Nagendra S. Evaluating variations in environmental noise pollution of Chennai city using a mobile monitoring technique. *J Transp Heal*. 2024;35(October 2023):101756. doi:10.1016/j.jth.2024.101756
25. Ramachandran S, Devadas D, Sivasankara Pillai G. Assessment of Noise Pollution in the City of Chennai. 2023;XXXII:40-54. doi:10.24205/03276716.2023.7005
26. Bouzir TAK, Berkouk D, Barrigón Morillas JM, Rey-Gozalo G, Montes González D. Noise Pollution Studies in the Arab World: A Scientometric Analysis and Research Agenda. *Sustain* . 2024;16(11). doi:10.3390/su16114350
27. Kumar V, Ahirwar A V., Prasad AD. A Review on Noise Pollution Monitoring, Mapping, Modelling, and Health Impacts. *J Environ Informatics Lett*. 2023;10(2):104-114. doi:10.3808/jeil.202300113
28. Basu B, Murphy E, Molter A, et al. Investigating changes in noise pollution due to the COVID-19 lockdown: The case of Dublin, Ireland. *Sustain Cities Soc*. 2021;65(November 2020):102597. doi:10.1016/j.scs.2020.102597
29. Hahad O, Rajagopalan S, Lelieveld J, et al. Noise and Air Pollution as Risk Factors for Hypertension: Part i - Epidemiology. *Hypertension*. 2023;80(7):1375-1383. doi:10.1161/HYPERTENSIONAHA.122.18732
30. Matsiko S, Ndoleriire C, Kakande E, et al. Noise-Induced Hearing Loss and Associated Factors Amongst Kampala City Traffic Police Officers. 2024;14(02):1-7.
31. Moroe N, Mabaso P. Quantifying traffic noise pollution levels: a cross-sectional survey in South Africa. *Sci Rep*. 2022;12(1):1-11. doi:10.1038/s41598-022-07145-z
32. Clark SN, Alli AS, Ezzati M, et al. Spatial modelling and inequalities of environmental noise in Accra, Ghana. *Environ Res*. 2022;214(July). doi:10.1016/j.envres.2022.113932
33. Osei FA, Effah EA. Health Effects caused by Noise - The Case of Africa: Evidence in Literature from the Past 25 Years. *Asian J Adv Res Reports*. Published online 2022:19-27. doi:10.9734/ajarr/2022/v16i230452
34. Joel M, Manaseh A, Enock K, Harriet N. Assessment of Road Traffic Noise in the Greater Kampala Metropolitan Area, Case Study of Namulanda-Kisubi Stretch, Entebbe Road. *Int J Traffic Transp Eng*. 2021;2021(2):25-36. doi:10.5923/j.ijtte.20211002.01
35. Kitamirike P. Effects of Noise on Urban Social Environmental Health in Kampala City: A Case Study of Selected Points in Kawempe Division. Published online November 12, 2022. Accessed January 22, 2025. http://dissertations.mak.ac.ug/handle/20.500.12281/14942
36. Nyembwe JPKB, Ogundiran JO, Gameiro da Silva M, Albino Vieira Simões N. Evaluation of Noise Level in Intensive Care Units of Hospitals and Noise Mitigation Strategies, Case Study: Democratic Republic of Congo. *Buildings*. 2023;13(2). doi:10.3390/buildings13020278
37. Omolo A, Angiro C, Wagaye WA, Olomo E, Okino J, Omara T. Aviation Noise and Air

Page **27** of **29**

Pollution: Results of a Study at Entebbe International Airport, Uganda. *OALib*. 2021;08(05):1-13. doi:10.4236/oalib.1107454

38. Samagwa D, Mkoma S, Tungaraza C. Investigation of Noise Pollution in Restaurants in Morogoro Municipality, Tanzania, East Africa. *J Appl Sci Environ Manag*. 2010;13(4). doi:10.4314/jasem.v13i4.55395
39. Umunnakwe JE, Ezirim KT, Chukwunyere NP. Noise Levels At Major Markets in Aba, Nigeria and Its Effects on Humans. *Int J Eng Technol*. 2020;3(6):5-16.
40. Agbo COA. Noise Pollution in Nigeria's Institutions of Higher Learning: A Review. *J Eng Res Reports*. 2020;18(1):8-21. doi:10.9734/jerr/2020/v18i117198
41. Akande OK, Yusuf A. Environmental Noise in Residential Environments: The Case for Quality of Life in Minna, Nigeria. *Environ Proc J*. 2022;7(22):117-125. doi:10.21834/ebpj.v7i22.4161
42. Samuel K, Yakubu S, Durowoju O. Noise in the City: A Socio-Spatial Analysis of the Actual and Perceived Noise Levels in a Medium-Sized Urban Center. *Coğrafya Derg / J Geogr*. 2024;0(47):1-13. doi:10.26650/jgeog2023-1276043
43. Clark SN, Alli AS, Nathvani R, et al. Space-time characterization of community noise and sound sources in Accra, Ghana. *Sci Rep*. 2021;11(1):1-14. doi:10.1038/s41598-021-90454-6
44. Egbenta IR, Uchegbu SN, Ubani E, Akalemeaku OJ. Effects of Noise Pollution on Residential Property Value in Enugu Urban, Nigeria. *SAGE Open*. 2021;11(3). doi:10.1177/21582440211032167
45. Clark SN, Alli AS, Brauer M, et al. High-resolution spatiotemporal measurement of air and environmental noise pollution in Sub-Saharan African cities: Pathways to Equitable Health Cities Study protocol for Accra, Ghana. *BMJ Open*. 2020;10(8):1-10. doi:10.1136/bmjopen-2019-035798
46. RPHC5_MainIndicatorsReport_Final.pdf.
47. World Bank. Rwanda economic update: Rethinking Urbanization in Rwanda: from Demographic Transition to Economic Transformation. 2017;11. http://documents.worldbank.org/curated/en/357911513632697178/pdf/122107-WP-PUBLIC-Rwanda-Economic-Update-FINAL.pdf
48. Nduwayezu G, Sliuzas R, Kuffer M. Modeling urban growth in Kigali city Rwanda. 2014;(2013).
49. Gilbert KM, Shi Y. Land use / land cover change detection and prediction for sustainable urban land management in Kigali City , Rwanda. 2023;3(2):62-75.
50. R Subramanian. Air pollution in Kigali, Rwanda: spatial and temporal variability, source contributions, and the impact of car-free Sundays. *Clean Air J*. 2020;30(2):1-15. doi:10.17159/caj/2020/30/2.8023
51. City of Kigali. Implementation Plan Kigali Master Plan 2050. *Syst Strateg Plan*. Published online 2020:139-142.
52. Sieber C, Ragettli MS, Brink M, et al. Land use regression modeling of outdoor noise exposure in informal settlements in Western Cape, South Africa. *Int J Environ Res Public Health*. 2017;14(10). doi:10.3390/ijerph14101262
53. Katalin Á. Studying noise measurement and analysis. *Procedia Manuf*. 2018;22(1):249-255.
54. WHO. 2 . Noise sources and their measurement 2 . 1 . Basic Aspects of Acoustical Measurements. *Guidel Community Noise*. Published online 1987:21-38. http://www.who.int/docstore/peh/noise/guidelines2.html
55. Energy A. Audible Noise in Switch Power Supply. :1-3.
56. Brink M, Schäffer B, Pieren R, Wunderli JM. Conversion between noise exposure indicators Leq24h, LDay, LEvening, LNight, Ldn and Lden: Principles and practical guidance. *Int J Hyg Environ Health*. 2018;221(1):54-63. doi:10.1016/j.ijheh.2017.10.003
57. Wunderli JM, Pieren R, Habermacher M, et al. Intermittency ratio: A metric reflecting short-term temporal variations of transportation noise exposure. *J Expo Sci Environ Epidemiol*. 2016;26(6):575-585. doi:10.1038/jes.2015.56

58. Brink M, Schäffer B, Vienneau D, et al. A survey on exposure-response relationships for road, rail, and aircraft noise annoyance: Differences between continuous and intermittent noise. *Environ Int*. 2019;125(January):277-290. doi:10.1016/j.envint.2019.01.043
59. Pollution NN, Level NP, Principles G, Facilities A. National Noise Pollution Guideline Contents. Published online 2016:8.
60. World Health Organization. WHO environmental noise guidelines for the European Region. Published online 2018.
61. van Kempen E, Casas M, Pershagen G, Foraster M. WHO environmental noise guidelines for the European region: A systematic review on environmental noise and cardiovascular and metabolic effects: A summary. *Int J Environ Res Public Health*. 2018;15(2):1-59. doi:10.3390/ijerph15020379
62. REPUBLIC OF RWANDA MINISTRY OF INFRASTRUCTURE NATIONAL TRANSPORT POLICY AND STRATEGY FOR RWANDA APRIL 2021 ii CONTENTS.
63. Baffoe G, Malonza J, Manirakiza V, Mugabe L. Understanding the concept of neighbourhood in Kigali City, Rwanda. *Sustain*. 2020;12(4):1-22. doi:10.3390/su12041555
64. Nshimiyimana AR, Niyigena E, Nyandwi E, Ngwijabagabo H, Rugengamanzi G. Spatial Assessment of Urban Growth on Green Spaces in Rwanda: An insight from Rebero Mountain Landscape in Kicukiro District, City of Kigali. *Rwanda J Eng Sci Technol Environ*. 2023;5(1). doi:10.4314/rjeste.v5i1.5
65. Oyedepo SO, Adeyemi GA, Fayomi OSI, et al. Dataset on noise level measurement in Ota metropolis, Nigeria. *Data Br*. 2019;22:762-770. doi:10.1016/j.dib.2018.12.049
66. Gongi SP, Kaluli JW, Kanali CL. Industrial Noise Pollution and its Health Effects on Workers in Nairobi City. *Int J Eng Res Technol*. 2016;5(9):426-435.
67. Acheampong PE, Amoah J. Assessment of Noise Levels and Perceptions of Its Health Impact at Kejetia Market in Ghana. Published online 2024:1-17.
68. Zhang H, Ye R, Yang H, et al. Long-term noise exposure and cause-specific mortality in chronic respiratory diseases, considering the modifying effect of air pollution. *Ecotoxicol Environ Saf*. 2024;282(May):116740. doi:10.1016/j.ecoenv.2024.116740
69. Baloye DO, Palamuleni LG. A comparative land use-based analysis of noise pollution levels in selected urban centers of Nigeria. *Int J Environ Res Public Health*. 2015;12(10):12225-12246. doi:10.3390/ijerph121012225
70. Wawa EA, Mulaku GC. Noise Pollution Mapping Using GIS in Nairobi, Kenya. *J Geogr Inf Syst*. 2015;07(05):486-493. doi:10.4236/jgis.2015.75039
71. Otieno Onyango D. Evaluation of the Extent and Potential Impacts of Noise Pollution inside Public Service Vehicles (PSVs) in Nairobi City, Kenya. *Am J Environ Prot*. 2015;4(5):260. doi:10.11648/j.ajep.20150405.17
72. Mahapa TP. Nightclubs and Restaurant Bars Noise Pollution : A Case Study of Melville Community , Johannesburg. 2017;9(10):47-55.
73. Mkoma SL. Noise Pollution on Wards in Iringa Regional Hospital , Tanzania Noise Pollution on Wards in Iringa Regional Hospital , Tanzania. 2014;(January 2010).
74. Lee EY, Jerrett M, Ross Z, Coogan PF, Seto EYW. Assessment of traffic-related noise in three cities in the United States. *Environ Res*. 2014;132:182-189. doi:10.1016/j.envres.2014.03.005
75. Xie J, Zhang G, Lee HM, Lim KM, Lee HP. Comparison of soundwalks in major European cities. *Appl Acoust*. 2021;178:108016. doi:10.1016/j.apacoust.2021.108016
76. Abdur-Rouf K, Shaaban K. Measuring, Mapping, and Evaluating Daytime Traffic Noise Levels at Urban Road Intersections in Doha, Qatar. *Futur Transp*. 2022;2(3):625-643. doi:10.3390/futuretransp2030034
77. Ko JH, Chang S Il, Kim M, Holt JB, Seong JC. Transportation noise and exposed population of an urban area in the Republic of Korea. *Environ Int*. 2011;37(2):328-334. doi:10.1016/j.envint.2010.10.001
78. Lee HM, Luo W, Xie J, Lee HP. Urban Traffic Noise Mapping Using Building Simplification in the Panyu District of Guangzhou City, China. *Sustain*. 2022;14(8):1-23.

doi:10.3390/su14084465
79. Barrigón Morillas JM, Rey Gozalo G, Montes-González D, Vílchez-Gómez R, Gómez Escobar V. Variability of traffic noise pollution levels as a function of city size variables. *Environ Res*. 2021;199(May). doi:10.1016/j.envres.2021.111303
80. Khomenko S, Cirach M, Barrera-Gómez J, et al. Impact of road traffic noise on annoyance and preventable mortality in European cities: A health impact assessment. *Environ Int*. 2022;162(February). doi:10.1016/j.envint.2022.107160
81. Apparicio P, Gelb J. Cyclists′ Exposure to Road Traffic Noise: A Comparison of Three North American and European Cities. *Acoustics*. 2020;2(1):73-86. doi:10.3390/acoustics2010006
82. Sakr A, El-Dars F, Hewehey M. Monitoring Noise Levels Along the Greater Cairo Urban Region Ring Road in Egypt. *J Environ Sci*. 2020;49(2):1-25. doi:10.21608/jes.2020.158105
83. Lee J, Gu J, Park H, et al. Estimation of populations exposed to road traffic noise in districts of Seoul metropolitan area of Korea. *Int J Environ Res Public Health*. 2014;11(3):2729-2740. doi:10.3390/ijerph110302729
84. Gong X, Fenech B, Blackmore C, et al. Association between Noise Annoyance and Mental Health Outcomes: A Systematic Review and Meta-Analysis. *Int J Environ Res Public Health*. 2022;19(5). doi:10.3390/ijerph19052696
85. Chan TC, Wu BS, Lee YT, Lee PH. Effects of personal noise exposure, sleep quality, and burnout on quality of life: An online participation cohort study in Taiwan. *Sci Total Environ*. 2024;915(December 2023):169985. doi:10.1016/j.scitotenv.2024.169985
86. MoE (2024). Instructions_on_noise_pollution_English_version.pdf.
87. Kheirbek I, Ito K, Neitzel R, et al. Spatial variation in environmental noise and air pollution in New York City. *J Urban Heal*. 2014;91(3):415-431. doi:10.1007/s11524-013-9857-0
88. Neitzel RL, Svensson EB, Sayler SK, Ann-Christin J. A comparison of occupational and nonoccupational noise exposures in Sweden. *Noise Heal*. 2014;16(72):270-278. doi:10.4103/1463-1741.140503
89. Esmeray E, Eren S. GIS-based mapping and assessment of noise pollution in Safranbolu, Karabuk, Turkey. *Environ Dev Sustain*. 2021;23(10):15413-15431. doi:10.1007/s10668-021-01303-5
90. Sanchez-Sanchez R, Fortes JC, Bolivar JP. Patterns to characterise the weekend effect on the environmental noise in coastal tourist towns. *Appl Acoust*. 2019;156:416-425. doi:10.1016/j.apacoust.2019.07.014
91. Martinez S, Sanchez R, Yañez-Pagans P. Getting a Lift: The Impact of Aerial Cable Cars in La Paz, Bolivia. *Economia*. 2024;23(1):204-229. doi:10.31389/eco.439
92. Garsous G, Suárez-Alemán A, Serebrisky T. Cable cars in urban transport: Travel time savings from La Paz-El Alto (Bolivia). *Transp Policy*. 2019;75:171-182. doi:10.1016/J.TRANPOL.2017.05.005
93. Prieto-Rodriguez J, Azuela-Flores JI, Groft D, Perez-Villadoniga MJ, Salas R. Assessing the impact of the new Mexico cable car on air pollution. *J Transp Geogr*. 2025;122(November 2023):104052. doi:10.1016/j.jtrangeo.2024.104052
94. Id HAL. The Cost and Benefits of Aerial Cable Cars Investment : A Case Study of Medellin City-Colombia To cite this version : HAL Id : hal-04519756 The Cost and Benefits of Aerial Cable Cars Investment : A Case Study of Medellin City-Colombia. Published online 2024.
95. Flesser M, Shalaby A, Friedrich B. Integration of urban aerial cable cars into public transit: Operational capacity limits due to passenger queuing at stations. *J Public Transp*. 2024;26(May):100094. doi:10.1016/j.jpubtr.2024.100094