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Spatio-temporal patterns of domestic water distribution, consumption and sufficiency: Neighbourhood inequalities in Nairobi, Kenya ☆

Nyamai Mutono [a,b,c,*], Jim Wright [d], Henry Mutembei [a,e], S.M. Thumbi [c,f,g]

[a] Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Upper Kabete, Kapenguria Road, P.O Box 30197, Nairobi, Kenya
[b] Washington State University Global Health Program, P.0 Box 72938-00200, Nairobi, Kenya
[c] Centre for Epidemiological Modelling and Analysis, Institute of Tropical and Infectious Diseases, University of Nairobi, Kenyatta National Hospital Campus, P.O Box 19676-00202, Nairobi, Kenya
[d] School of Geography and Environment Science, University of Southampton, Shackleton Building 44, Highfield Southampton, SO17 1BJ, UK
[e] Department of Clinical Studies, University of Nairobi, Nairobi, Kenya
[f] Institute of Immunology and Infection Research, School of Biological Sciences, University of Edinburgh, The King's Buildings, Charlotte Auerbach Road, Edinburgh, EH93FL, UK
[g] Paul G. Allen School for Global Health, Washington State University, P.O Box 647090-99164, Pullman, USA

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ABSTRACT

Whilst there are longstanding and well-established inequalities in safe-drinking water-access between urban and rural areas, there remain few studies of changing intra-urban inequalities over time. In this study, we determined the spatio-temporal patterns of domestic piped water distribution in Nairobi, Kenya between 1985 and 2018, and the implications of socio-economic and neighbourhood inequalities in water sufficiency. Using data from the Nairobi water and sewerage utility company for the period 2008–2018, we examined the sufficiency of monthly domestic water consumption per capita for 2380 itineraries (areas with an average population of 700) in relation to a residential neighbourhood classification, population and neighbourhood age and also examined water rationing patterns by neighbourhood type. Water sufficiency differed by residential areas, age of neighbourhood and population per itinerary. Compared to residents of low-income areas, those in high- and middle-income areas were six and four times more likely to receive the recommended 1500 L per capita per month respectively. Newer neighbourhoods and less densely populated areas were more likely to receive higher volumes of water. Non-revenue water loss accounted for 29% (average 3.5 billion litres per month) of water distributed across Nairobi, and was more than two times the amount of water needed for all residents to access the recommended monthly per capita water consumption. The observed spatial inequality in distribution, and access to piped water associated with socio-economic status and neighbourhood age highlights the need for deliberate planning and governance to improve water distribution to match the speed of growth of low/middle- and low-income residential areas and enhance equity.

1. Introduction

Many cities struggle to supply water to their residents both due to rapid population growth through urbanisation, and in some regions, because of water scarcity (UNESCO & UN-Water, 2020). Revenue recovery among low-income neighbourhoods can be challenging, as can service delivery in unplanned, informal neighbourhoods (Dagdeviren & Robertson, 2011). There is concern that progress in informal urban neighbourhoods lags substantially behind formal neighbourhoods, and that data aggregated to city scale may mask such localised variation in the progress to widening access to safe drinking water (Cetrulo et al., 2020).

To ensure monitoring of the Sustainable Development Goals (SGDs), the Joint Monitoring Programme (JMP) routinely measures inequalities from cross-sectional household surveys and censuses at national level, with several studies having used such data to examine inequalities in

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* Corresponding author. Wangari Maathai Institute for Peace and Environmental Studies, University of Nairobi, Upper Kabete, Kapenguria Road, P.O Box 30197, Nairobi, Kenya.

E-mail address: mutono.nyamai@wsu.edu (N. Mutono).

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water access at household level through to national scale (Adams, 2018; Chaudhuri & Roy, 2017). However, studies of changing inequalities over time remain scarce at the sub-national and particularly the city scale, given this reliance on cross-sectional data sources.

Inequalities in safe water access are frequently measured through source type (often classified according to the JMP's ladder), such as access to tap water (Malakar et al., 2018). Some studies have incorporated other dimensions of water service delivery, notably water quality (Yang et al., 2013), but there are relatively few studies that have examined intra-urban differences in volumes of water consumed (Adams, 2018). This is despite recognition via the incorporation of safely managed water services into SDG 6.1.1. Safely managed water services recognise the importance of providing water on premises, the availability of water when needed (and implicitly having sufficient volumes of water to meet basic needs), its safety and affordability. Those that have studied transition of safer water access typically rely on the type of source used, for example, improved versus unimproved for Nairobi (Iddi et al., 2021).

In low-income urban areas, relatively low water consumption rates per household make water provision there less commercially attractive than in middle or high-income areas (Boakye-Ansah et al., 2019). This is particularly so where low volume consumers benefit from reduced tariffs per cubic metre via progressive tariff structures (Castro & Morel, 2008). The risk to service providers is further exacerbated by greater illegal connection rates and non-revenue water in such areas. In many low and middle income countries (LMIC) cities, expansion of low-income neighbourhoods is unplanned, spontaneous and unregulated, with large proportions of Sub-Saharan Africa's urban population living in such informal settlements (Castro & Morel, 2008). This unplanned nature of low-income urban growth is a further challenge for water service delivery (Boakye-Ansah et al., 2019).

Given the paucity of studies at the city scale of changing inequalities in water access, the objectives of this study are therefore to examine inter-neighbourhood variation in sufficiency of domestic water consumed in relation to neighbourhood type and age, and how these data have changed over time. In examining neighbourhood age, we seek to understand the extent to which service delivery may be delayed or impacted in newly developed low-income urban neighbourhoods. In doing so, we draw on utility consumption records for the city of Nairobi, Kenya, disaggregated to fine spatial resolution, supplementing these with ancillary geospatial data to characterise Nairobi's neighbourhoods at fine spatial resolution.

2. Materials and methods

2.1. Study setting

Nairobi is the largest city in Kenya with an estimated 4.4 million people (Kenya National Bureau of Statistics, 2019). It is one of the 47 counties in Kenya and covers an area of 645 km^2 with a population density of 6247 people per km^2. The estimated population growth of Nairobi is 4% annually (World Bank, 2020).

2.1.1. Water sources, treatment, and distribution network

Constituted as a company in 2003, Nairobi City Water and Sewerage Company (NCWSC) is responsible for water production and distribution in Nairobi. NCWSC is the sole distributor of piped water in the city and is charged with the mandate of equitably providing clean water and sewerage services to the residents of the city.

Nairobi receives its water from three dams (Ruiru dam, Sasumua dam, Thika dam) and one water spring (Kikuyu Springs). The three dams receive water from rivers that originate from the Aberdare Ranges. The Kikuyu water springs recharge from an aquifer in the Limuru area in Kiambu County neighbouring Nairobi.

Kikuyu springs: This was the first and main source of safe drinking water for residents of Nairobi between 1901 and 1950. The springs recharge from an aquifer estimated to cover 161 km^2 with an annual recharge of 13.2 billion litres. The water from the springs is chlorinated at the source and discharged to the Kabete service reservoir before onward distribution to the Nairobi city residents. Half (51%) of the water in Kikuyu Springs is abstracted through boreholes (Water Resources Authority, 2018).

Ruiru dam: This is the oldest of the three dams. Its construction was finalised in 1950 becoming the second main source of water supplied in Nairobi County after Kikuyu Springs. The dam receives water from the Ruiru river and transmits the untreated water to Ruiru junction where it is mixed with the treated water from Sasumua dam and transmitted to the Kabete service reservoir.

Sasumua dam: This is the second oldest of the three dams. Located on the Sasumua stream, a tributary of the River Chania, the dam became functional in 1956. The dam transmits raw water to the Sasumua treatment plant. The treated water is transmitted to Kabete service reservoir via Ruiru junction where it is combined with raw water from Ruiru dam.

Thika dam: This is the newest of the three dams, becoming operational in 1994 (Olima & K'Akumu, 1999). With a reservoir capacity of 70 billion litres, Thika dam is the largest of the three dams that supply water to Nairobi. The dam receives water from three sources: Thika river which provides 50% of the water, Githika river (30%) and Kayuyu river (20%). The raw water from Thika dam is transferred to Chania River through a tunnel with additional flows from Kiama and Kimakia weirs. The water in Chania River is then abstracted through another tunnel that is also fed by water from Mwagu weir and transmitted to Ngethu water treatment plant. After treatment, the water is transmitted to Gigiri service reservoir in Nairobi County.

Fig. 1 shows the locations of the main sources of water for Nairobi, the treatment plants, and the distribution network of the piped water in the city.

Water transmission from the dams and the springs to the service reservoirs is gravity-fed. Of the four water sources for Nairobi County, only Sasumua and Thika dams have the capacity to treat the raw water (Sasumua and Ngethu treatment plants respectively) before transmission to the two main service reservoirs (Gigiri and Kabete) for the city. The Gigiri and Kabete service reservoirs, with a daily gross yield of 401 and 77.6 million litres respectively, serve as water treatment sites before piped distribution to the consumers.

The treatment process at the service reservoirs and the water treatment plants near the dams starts with sedimentation either through the horizontal-flow or vertical-flow process. The water then goes through rapid gravity sand filtration, disinfection through chlorination and pH adjustment by the addition of soda ash (anhydrous sodium carbonate). The last step is coagulation using alum (hydrated double sulphate of aluminium and potassium). The treated water is then distributed from the service reservoir to the consumers.

The Gigiri service reservoir, which distributes 84% of the piped water consumed in Nairobi County, pumps 8% (32 million litres/day) of its water to Kabete service reservoir to meet shortfall in supply from Kabete sources. Kabete service reservoir mainly distributes water to the central and western parts of the city. The eastern side of the city mainly receives water from Gigiri service reservoir.

Eleven minor service reservoirs, six from Gigiri service reservoir (Kiambu, Karura, Kasarani, Outering, Wilson, Embakasi) and five from Kabete service reservoir (Kyuna, Dagoretti Forest, Uthiru, Hill Tank, Loresho) distribute water across the city. The water is pressurised through pump stations (Kabete, Gigiri, Kenyatta Avenue, Loresho) at different points of the distribution network (Fig. 1).

A summary of the characteristics of the four main sources of water for Nairobi County is provided in Table 1.

2.1.2. Water distribution by residential classification

The initial water distribution network for Nairobi was centred on the different residential areas that were using the Kabete service reservoir

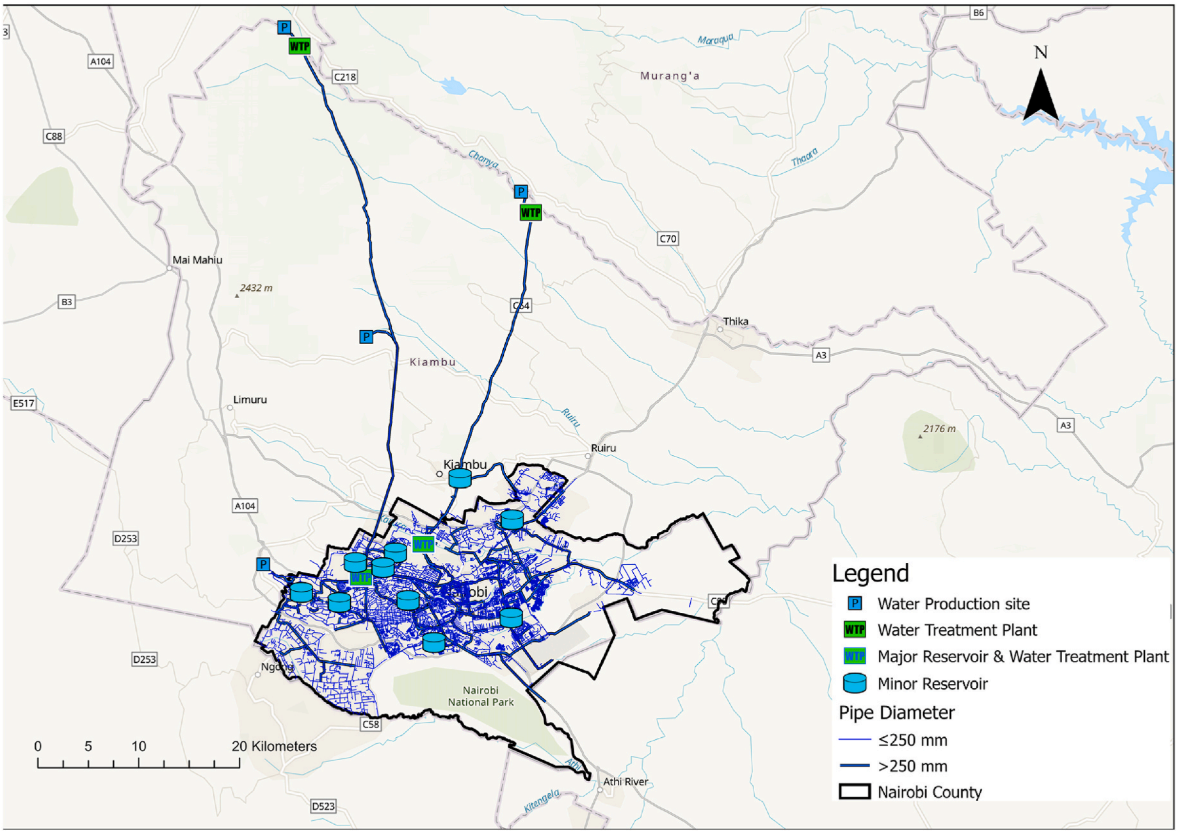

Fig. 1. *Piped water distribution system for Nairobi County showing water sources, treatment plants, water diameter pipelines and water service reservoirs. Source: Open Street Map* (Haklay & Weber, 2008). *Shapefile Source: Database of Global Administrative Areas* (GADM, 2020).

Table 1
Characteristics of the main sources of piped water supplied in Nairobi County.

Parameter	Thika Dam	Sasumua Dam	Ruiru Dam	Kikuyu Springs
Year of operation	1994	1956	1950	1901
Height (metres)	65	42	23	Not applicable
Source of water	River Thika, River Githika, River Kayuyu	Sasumua stream	River Ruiru	Kikuyu Springs Aquifer
Reservoir/ recharge capacity (million litres)	70,000	19,000	3000	13,000
Gross yield capacity (litres/day)	460,000,000	59,000,000	22,700,000	4,800,000
Daily transmission (litres/day)	430,000,000	56,200,000	21,700,000	1,440,000
Capacity utilised	93%	95%	96%	30%
Treatment plant	Ngethu water treatment works	Sasumua treatment works	None	Chlorination at the springs
Major service reservoir served[a]	Gigiri	Kabete	Kabete	Kabete

Source: Nairobi City Water and Sewerage Company, Global Reservoir and Dam Database (Lehner et al., 2011).
[a] Additional water treatment happens at the major service reservoir before distribution.

(van Zwanenberg, 1975). To cater for the increase in population, the first comprehensive water distribution plans were developed in 1985 by the Water and Sewerage department of the Nairobi City Commission. These plans used the residential area categories in the 1979 land use maps that were derived from the 1973 Nairobi Metropolitan Growth Strategy (Kingoriah, 1983).

The residential areas were divided into four categories (Residential areas 1–4) based on income, population density and type of housing. Residential areas 1 (R1) were the high-income areas characterised mainly by detached houses and modern houses often with medium to large gardens, low population density of less than 5000 people per square kilometre and residents earning a monthly income of more than $29 per household. Residential areas 2 (R2) were the middle-income areas characterised by housing estate developments and flats, mixed with small commercial areas and a medium population density of 6000–8000 people per square kilometre. The residents had a monthly income of between $11 and $29 per household. Residential areas 3 (R3) were the middle/low income areas characterised by flats and houses in older city areas, mixed with small commercial and light industrial areas and a medium to high population density of 9000 to 11,000 people per square kilometre. Residential areas 4 (R4) comprised of areas with low-income housing and unauthorised shanty dwellings and a high population density of more than 11,000 people per square kilometre. The monthly income of residents in R3 and R4 was $6 to $11 and below $6 respectively. High- and middle-income areas predominantly accessed piped water through direct household connections while middle/low and low-income areas primarily accessed piped water through shared taps at yard/compound and water kiosks respectively.

Over the years, the type of piped water access has been maintained while the water distribution in the city has been updated by adding new customers to the network, with residential areas developed after 1985 being assigned to one of the four existing residential categories. In 2018, the land use maps were updated using the 2014 Nairobi Integrated Urban Development Master Plan that incorporated the 1973 Master Plan, the growth in population and the land use changes between 1979 and 2014 (Nairobi City County, 2014).

To enable easy control and monitoring of the amount of water distributed for billing purposes and the process of adding more customers to the system, the NCWSC groups water customers into small geographical units referred to as itineraries. Each itinerary has an average of 700 people. During periods of water shortages, NCWSC rations the water by having programs on number of hours and days itineraries are supplied with water per week. The rationing programs are revised every six to twelve months, with occasional delays.

2.1.3. Domestic tariff structure for water produced by NCWSC

The water tariff structure for Nairobi is prepared by the Nairobi City Water and Sewerage Company. This tariff remained unchanged for the periods of 2015–2018. For water supplied to residential areas through direct household connections, a flat rate of US $1.89 was charged for monthly water consumption of <7000 L. Monthly consumption between 7000 and 60,000 L was charged at US $0.49 per 1000 L. Additional consumption above 60,000 L was charged at US $0.59/1000 L.

For water supplied to shared taps in yards/compounds and to water kiosks, the recommended retail price was $0.49 and $0.19 per 1000 L respectively. However, the water kiosks were privately owned and NCWSC was only able to recommend but not enforce the water rates.

2.2. Data sources

To understand the water distribution patterns for Nairobi County, we obtained data from NCWSC on the monthly water outflows for the main reservoirs that distribute water across Nairobi, data on volumes of water consumed in every itinerary, water rationing programs and population of every itinerary for the period 2008 to 2018. We also collected the geographical locations of the itineraries and the 1985 and 2018 water distribution networks for Nairobi from NCWSC.

The population counts, density, monthly water production (water from the reservoirs), water distribution network, water access for the residential categories, volumes of monthly water consumption of piped water in every itinerary, monthly unit cost of water, water rationing data, geographical location of the itineraries and land use maps for 1985 were obtained from NCWSC. The land use maps for 2018 were obtained from the Kenya Ministry of Lands and Physical Planning. The data on water production was only available for the period November 2016 (when metering of this water started) to May 2018 (when breakages in the metering system happened).

The water consumption data for Nairobi is collected on a monthly basis from the customer's meter readings and used to bill the consumers. This data was aggregated to itineraries in order to de-identify the customers. Of the 3000 itineraries, 15% (n = 554), which consisted of non-residential (20%, n = 462) and residential (20%, n = 92) itineraries, were filtered out due to lack of a geographical location, leaving 85% (n = 2538) of itineraries grouped into either residential (n = 2380, 94%) or non-residential (n = 158, 6%) areas.

Gridded population data for each year from 2008 to 2018 were obtained from WorldPop (WorldPop, 2019). To calculate this population, WorldPop derive data from official country census data, administrative boundary maps and ancillary geospatial data sets such as road networks, hospital facilities, satellite imagery and buildings or settlements maps. Aggregate population counts for census areas are re-distributed within each boundary onto constituent 100 by 100 m grid cells. A random forest dasymetric mapping algorithm is used by WorldPop to predict the population in every 100 by 100 m grid cell from covariates such as distance to urban areas, bare areas, settlement build-up areas, water bodies, roads and night-time lights among others. The covariates are weighted and used to project population to the grid cells which is then aggregated to administrative boundaries and the accuracy assessed using predictions from freely available population datasets which include the Global Rural Urban Mapping Project and the Gridded Population of the World (Reed et al., 2018; Stevens et al., 2015). Annual population estimates are derived from a built-settlement growth modelling framework alongside successive census population estimates (Nieves et al., 2020).

To understand the association of neighbourhood age with volumes of water consumed per person per month, we acquired spatial data from the Global Human Settlement (GHS) project. The project categorises settlement typologies using built-up land cover based on the classification of the degree of urbanisation, as either cities, towns and suburbs or rural areas according to geographical contiguity (Florczyk et al., 2019). We used the GHS-Built map layer, which identifies the period when 30 × 30 m grid cells were converted to built-up land cover, based on multi-temporal classification of Landsat imagery from 1975, 1990, 2000, and 2014.

To evaluate the Nairobi Water and Sewerage Company's residential classification's suitability for inequality assessment, we obtained data at a sublocation level from the 2012–2013 Kenya State of the Cities Baseline Survey (KSCBS) (World Bank Group, 2014, pp. 68–70). This multi-stage cluster survey measured household service access and socio-economic characteristics in 15 Kenyan cities in a representative sample of sub-locations. Data concerning 1137 household respondents within seven sublocations in Nairobi were included in the analysis.

2.3. Data analysis

We calculated the population for every itinerary by carrying out spatial queries of the population raster files using Quantum Geographic Information System (QGIS) (QGISDevelopment Team, 2016). We compared population counts and density in 1985 when the water distribution network was developed with that of 2018. We analysed population trends within the four residential area types between 2008 and 2018. In addition, we calculated the per capita monthly water consumption for the different itineraries and examined spatial patterns of water sufficiency (defined as >1500 L per capita/month) across the study period.

Since small area statistics at sublocation level are unavailable for either the 2009 or 2019 Kenyan population census, we used the utility's residential classification to examine neighbourhood inequalities in monthly water consumption over time. To evaluate the classification as a proxy for the socio-economic status of different neighbourhoods, we first cross-tabulated utility residential classes against household characteristics in the KSCBS by linking itinerary boundaries to KSCBS sublocation boundaries. Household characteristics examined largely reflected UN-Habitat slum criteria (UN-HABITAT, 2018) and included security of tenure, type of toilet facility predominantly used by the household, durability of housing structure, and use of a storage tank with a capacity of more than 100 L.

We calculated the total water distributed in Nairobi County and the per capita monthly water consumption in the four residential areas, analysed the proportion of residents in the different categories who had a monthly water consumption of more than 1500 L/capita/month and the non-revenue water for Nairobi County. In addition, we carried out a negative binomial linear mixed-effects model (with year as a random effect) to determine if there were differences in the monthly per capita water consumption among the four residential categories over the study period, the yearly population in the itinerary, age of the residential neighbourhood, classified into five ordinal values based on the predominant period when the itinerary's land cover became built-up (before 1975, 1975 to 1990, 1990 to 2000, 2000 to 2014, after 2014). Univariable model analysis was carried out and independent variables with a p value < 0.2 were included into the multivariable model. The collinearity of the different independent variables in the model was carried out using the Variance Inflation Factor (VIF) method. Factors with a VIF of more than five were termed as highly correlated and their interaction was assessed with other independent factors, where those that had a VIF of less than three was retained (Zuur et al., 2010). We carried out model diagnostics by calculating scaled residuals and mapped residuals to check for patterns. We also tested for dispersion of residuals, spatial and temporal autocorrelation in residuals to see if there was over/under dispersion, any spatially or temporal correlated structure in the model that was unaccounted for respectively. The analysis was performed using the R statistical software (R Core Team, 2017).

3. Results

3.1. Residential areas and population size

The comparison of the characteristics of the 1985 and 2018 land use categories that guide water distribution in Nairobi showed a marked change in the population size and area size covered by each of the four categories. In 1985, the total residential area was 190 km^2, covering 29% of the total land in Nairobi County. By 2018, this area had increased by 115%–408 km^2, with the total residential area covering 63% of Nairobi County (Table 2).

The middle/low-income residential category had the largest growth in area over the period (a five-fold increase) followed by the middle-income residential areas (a two-fold increase). This increase was mainly through conversion of areas previously designated as agricultural or open spaces to residential areas to accommodate the increase in population size (Fig. 2). In terms of the proportion of the residential areas in Nairobi occupied by the various residential categories in 1985 and 2018, the largest increase was observed in middle/low-income areas (changing from 20% to 46%), and the largest decrease in the high-income areas (changing from 51% to 28%), Table 2.

Between 1985 and 2018, the Nairobi population increased by 278% from 1,162,000 to 4,197,880 people. During this period, the largest increases in population size by residential areas were observed in the low-income category (growing 4.4 times), and middle/low-income areas (2.9 times). Population growth in the high-income and middle-income areas was 0.7 times and 1.62 times respectively (Table 2). Almost a third (31%) of this population growth was due to shifts in classification areas. Pre-1986 non-residential areas transitioned to areas that were now converted to middle/low-income areas (16%, 659,154), middle-income areas (7%, 284,848), low-income areas (6%, 240,209) and high-income areas (1% 47,807). Furthermore, a small proportion of the middle/low (2%, 88,649), middle (1%, 40,189) and high (0.3%, 13,685) income areas transitioned to areas classified as low-income areas.

Table 2
Characteristics of the different residential areas in Nairobi County in 1985 and 2018.

Parameter	High income areas (R1) (%)	Middle income areas (R2) (%)	Middle/low income areas (R3) (%)	Low income areas (R4) (%)
Total area (km^2)				
1985	96.57 (51%)	36.02 (19%)	37.89 (20%)	19.44 (10%)
2018	113.05 (28%)	75.81 (19%)	189.23 (46%)	29.55 (7%)
Total population				
1985	139,000 (12%)	289,000 (25%)	460,000 (40%)	274,000 (23%)
2018	237,135 (6%)	757,393 (18%)	1,780,172 (42%)	1,423,180 (34%)
Minimum or maximum ranges of population density (people/km^2)				
1985	<5000	6000–8000	9000–11,000	>11,000
2018	<4500	4500–13,500	13,500–18,000	<18,000
Range of household income ($)				
1985	>29	11–29	6–11	<6
2018	>1800	900–1800	360–900	<360
Water connection type				
1985	Inhouse connection	Inhouse connection	Shared pipes at tap/yard	Water kiosks
2018	Inhouse connection	Inhouse connection	Shared pipes at tap/yard	Water kiosks

Source: Nairobi City Commission (Nairobi City Commission, 1985)*; WorldPop* (WorldPop, 2019); *Economic Survey 1985* (Central Bureau of Statistics, 1985); *2019 Kenya Population and Housing Census* (Kenya National Bureau of Statistics, 2019); *Africa Development Bank* (African Development Bank, 2011).

In 1985*,* monthly household income was classified as below $6 for low-income areas and above $29 for high income areas. By 2018, the classification had changed to above $1800/month for high income areas while the low-income areas were classified as having a monthly revenue of less than $360 per month. The monthly income classification for middle and middle/low-income areas had moved from $11-$29 and $6-$11 in 1985 to $900-$1800 and $360-$900 respectively (Table 2). Over the years, the primary water connection type in the residential categories has remained the same, with high- and middle-income areas accessing water through inhouse piped connection whereas the middle/low and low-income areas accessing water through shared taps at yard and water kiosks respectively.

Comparison of the 2008 and 2018 population size in Nairobi shows a substantial change in the population of each of the four residential area categories. In 2008, the total population was 3 million, with middle/low and low-income areas comprising 43% and 28% respectively. This population had increased by 48% to 4.2 million by 2018 where three quarters of the population resided in both the middle/low (42%) and low-income areas (34%). The largest growth in population was observed in low-income areas and middle-income areas which had increased by 75% and 58% respectively. The population in middle/low-income areas had increased by 45%, while that in high income areas had decreased by 25% (Fig. 3).

Compared to the previous year, a substantial population change was observed in 2013 in both high- and low-income areas, where there was a decrease of population by 42% (158,198) in high income areas and a 37% (371,020) increase in population in low-income areas (Fig. 3).

3.2. Temporal patterns of production, non-revenue water and consumption

Data on water distribution in Nairobi County was available for the period 2008–2018. During this period, the total amount of water distributed increased gradually with residential areas consuming most of the water (82%) distributed by NCWSC, with non-residential areas only consuming 18% (Fig. 4). The spikes observed are associated with rainy seasons (usually in March to May and November to December) during the study period. During periods of high rainfall, the utility company fully draws water from the rivers and only switch to discharging water from the dams when the rains recede. Maximum distribution of water from the dams continue until the levels are at 60% of the dam height when the rationing programmes are re-introduced.

In late 2012/2013 and 2014/2015, there were engineering modifications done at the treatment plants which included the increased height for the water filters and a total overhaul of the air valves along the transmission lines, resulting in increased water flows for treated water distributed in the city. These replacements are periodical with decreased efficiency of the transmission lines between replacement times.

Data on non-revenue water lost through illegal connections, pipe bursts, water leakages, unmetered and irregular meters was only available for the period 2016–2018 (Fig. 4). These data are calculated based on the amount of water released from the reservoirs and amount of water billed for by NCWSC. The non-revenue water loss averaged 3.5 billion litres of water per month, accounting for 29% of all water distributed across Nairobi County.

3.3. Residential water consumption by neighbourhood type

Comprehensive data on water rationing was available for the period 2016 to 2018. From these data, low-income areas recorded the highest number of hours receiving water while middle-income areas had the

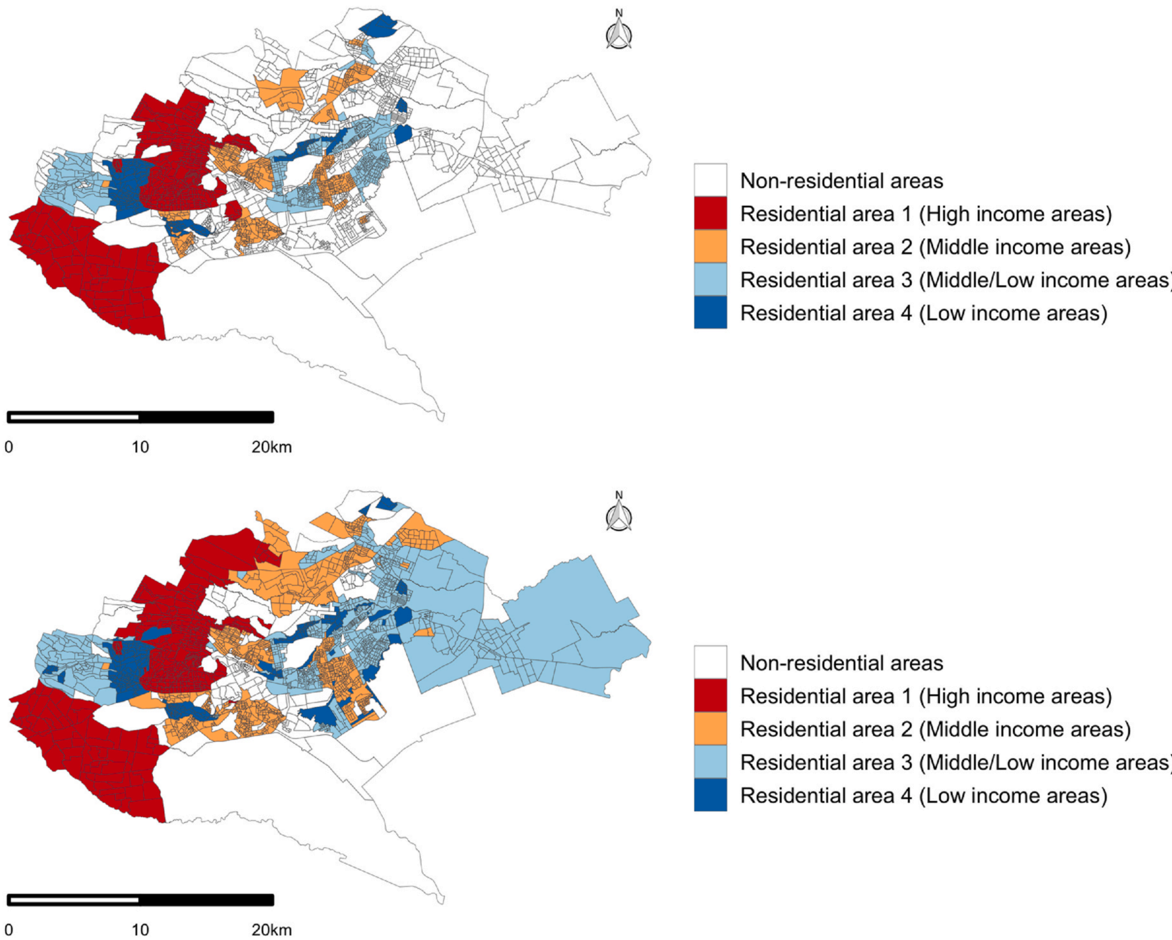

Fig. 2. Residential and non-residential areas in Nairobi County in 1985 versus 2018. Source: Nairobi City Water and Sewerage Company, Survey of Kenya, Ministry of Lands and Physical Planning. Shapefile Source: Database of Global Administrative Areas (GADM, 2020).

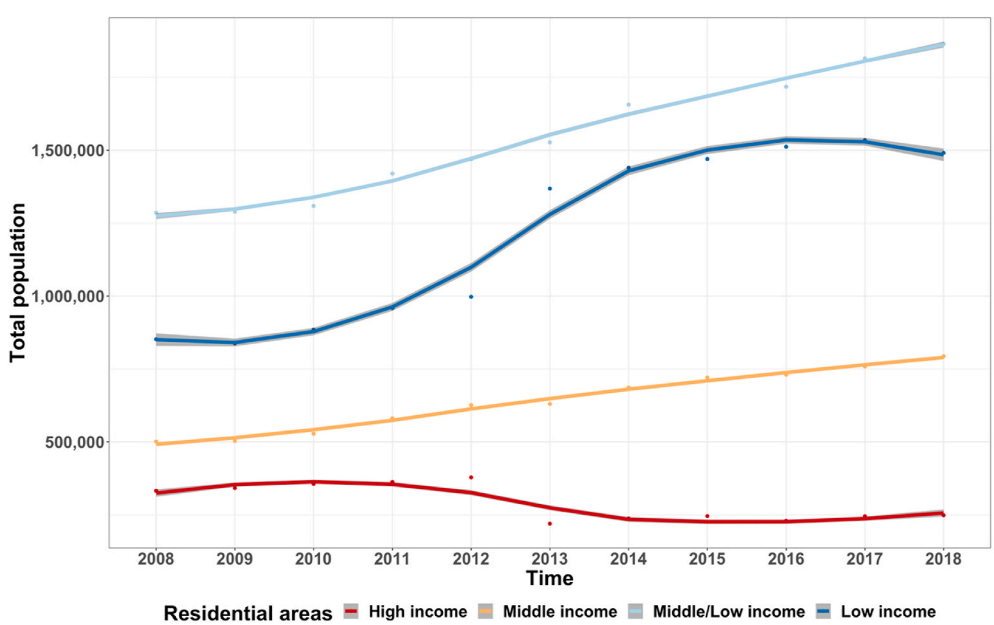

Fig. 3. Population of the residential areas in Nairobi County from 2008 to 2018, classified by residential area type. Source: WorldPop and Nairobi City Water and Sewerage Company.

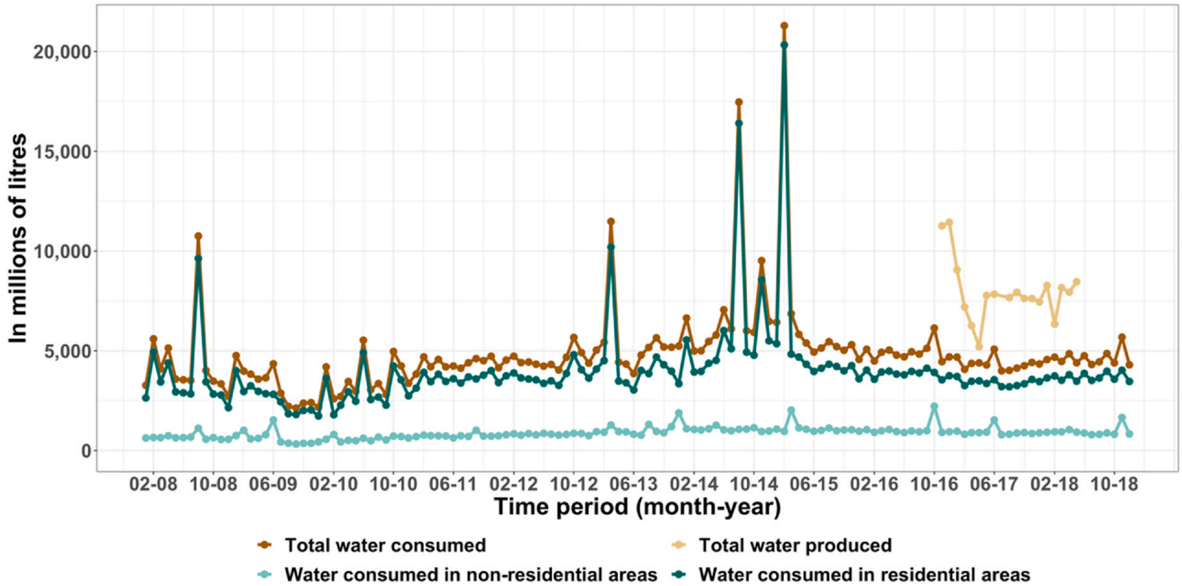

Fig. 4. Residential versus non-residential monthly piped water consumption across Nairobi County from 2008 to 2018. The data for the total water consumed was only available for the period when the metering system at the major service reservoirs was functional.

Table 3
Average hours of weekly water supply per residential category in Nairobi County from October 2016 to December 2018 as per the water rationing programs.

Period for water rationing programs	High-income areas (R1) (days)	Middle-income areas (R2) (days)	Middle/low income areas (R3) (days)	Low-income areas (R4) (days)
July–December 2018	58 h (2.4)	49 h (2)	65 h (2.7)	82 h (3.4)
May–June 2018	54 h (2.3)	44 h (1.8)	58 h (2.4)	68 h (2.8)
January 2018–April 2018	54 h (2.3)	45 h (1.9)	58 h (2.4)	68 h (2.8)
October 2016–December 2017	69 h (2.9)	61 h (2.5)	78 h (3.3)	93 h (3.9)

least number of hours. On average, the residents, starting from the high-income areas to low-income areas received water continuously for 59 h (2.5 days), 50 h (2.1 days), 65 h (2.7 days) and 78 h (3.3 days) respectively per week (Table 3). However, data on water consumption patterns shows the residents living in high- and middle-income areas had a monthly per capita water consumption of 13,087 L and 6240 L respectively. Only a small proportion of residents in high-income (7%) and middle-income areas (12%) received less than the recommended 1500 L per capita per month.

The residents in low/middle income areas had a monthly per capita water consumption of 1697 L while low-income residents had a consumption of 827 L. During the study period, an estimated 36% of the residents in low/middle income areas and 60% of residents in low-income areas had insufficient monthly consumption of piped water. These two residential area categories were at risk of water insufficiency with more than a third of their population constantly having per capita monthly water consumption of less than the recommended 1500 L

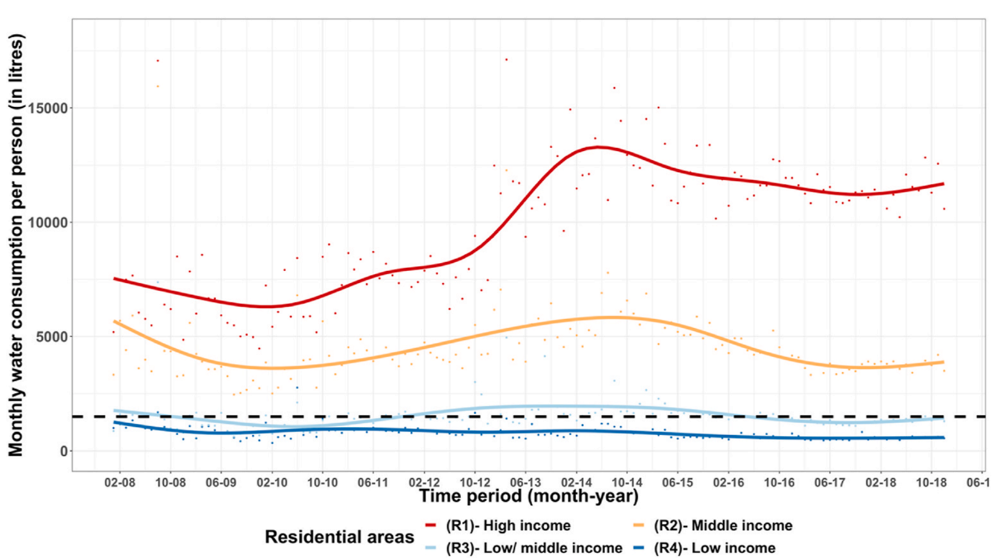

Fig. 5. *Water consumption* per *person in the four different residential categories. The dashed line shows minimum water requirements for domestic purposes (1500 L/capita/month as* per *Gleick* (Gleick, 1996)*), while the dots are the monthly average water consumption in the itineraries* per *residential area type.*

(Fig. 5). To ensure everyone had a continuous sufficient water consumption of at least 1500 L, an additional 1.5 billion litres/month would be required, an amount less than the estimated monthly non-revenue water.

3.3.1. Spatial-temporal distribution of water in Nairobi County

Visualisation of the spatial and temporal distribution of water in Nairobi County between 2008 and 2018 revealed several key patterns. First, for most years, water sufficiency was achieved for most residents in the periods between July and September (Fig. 6). Secondly, there were spatial differences in water sufficiency with certain residential areas constantly experiencing water sufficiency while others were almost always insufficient. Thirdly, water insufficiency was higher during the later years of the study period with water insufficiency highest (83% of the year) in 2017, which was a severe drought period (Mwangi et al., 2014) and lowest in 2009 and 2010. From 2015 to 2018, the majority of residents had experienced water insufficiency for two thirds of the year (Fig. 6).

We used the per capita monthly consumption to determine if there were significant differences in water sufficiency among the residential categories and the age of the residential neighbourhoods. We observed that, compared to residents in low-income areas, the likelihood of getting sufficient volumes of water per capita per month was six times (CI: 5.34–6.25) higher in high income areas, four times (CI: 3.52–4.10) in middle income areas and twice in middle/low-income areas (CI: 1.53–1.79) (Table 4). We found significant associations between the age of the residential neighbourhoods, interaction between age of residential neighbourhoods and the residential categories and population. Water consumption patterns were higher in newer neighbourhoods and areas with a lower population (Table 4). Additionally, the interaction between the age of the neighbourhood and residential category demonstrated higher likelihood in water sufficiency in the high- and middle-income areas, compared to low-income areas. The results of the goodness of fit tests on the model residuals included test dispersion of 0.873, temporal and spatial autocorrelation test of 0.267 and 0.028 respectively and zero unaccounted patterns both in the temporal and spatial graphs outputs. Similarly, the log likelihood ratio of the model was less than 0.001.

Comparison of the utility's residential classes with KSCBS household data suggested residential class was a reasonable proxy for socio-economic status (Supplemental Materials, Table 1A). For example, proportion of households with secure tenure was 85% in the high-income residential class, but 48% in the low-income class. Similarly, the use of a storage tank with the capacity of more than 100 L was 77% in the high- and middle-income areas but only 64% and 36% in the middle/low and low-income areas respectively. Flush toilets were predominantly used in the high (90%) and middle (84%) income areas while in only 52% and 34% of the middle/low and low-income areas respectively. Compared to the high- and middle-income areas, the use of shared pit latrines was relatively higher in low (49%) and middle/low (39%) income areas. Almost all the residents in high income areas (93%) had permanent household structures but only 45% in the low-income areas.

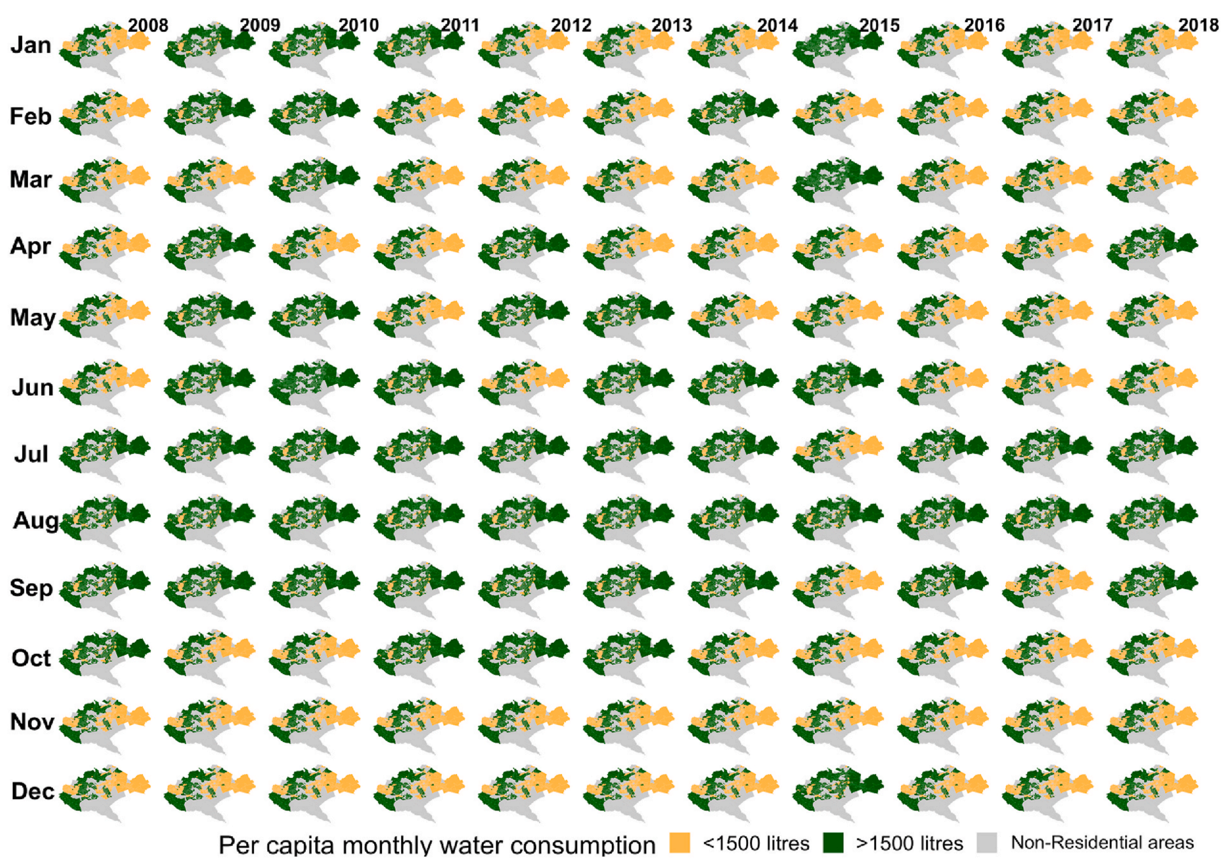

Fig. 6. *Spatial distribution of average* per capita *monthly water consumption for residential areas in Nairobi County from 2008 to 2018. Shapefile Source: Database of Global Administrative Areas* (GADM, 2020).

Table 4
Analysis of the monthly per capita water consumption by residential categories, age of built settlements and population for 2380 water distribution itineraries for Nairobi.

Parameter	Number of itineraries per category (%)	Rate Ratio (p Value)	Confidence Interval
Residential category			
High-income areas	534 (22%)	5.78 (<0.001)	5.34–6.25
Middle-income areas	772 (32%)	3.80 (<0.001)	3.52–4.10
Middle/low-income areas	822 (35%)	1.65 (<0.001)	1.53–1.79
Low-income areas	252 (11%)	Reference category	
Built settlements			
Built up before 1975	579 (24%)	0.54 (0.425)	0.53–0.56
Built from 1975 to 1990	184 (8%)	0.62 (<0.001)	0.60–0.65
Built from 1990 to 2000	965 (41%)	0.87 (<0.001)	0.85–0.89
Built from 2000 to 2014	434 (18%)	0.96 (<0.001)	0.94–0.99
Built up after 2014	218 (9%)	Reference category	
Built up before 1975			
High-income areas	281 (48%)	2.85 (<0.001)	2.80–2.90
Middle-income areas	116 (20%)	2.34 (<0.001)	2.28–2.40
Middle/low-income areas	108 (19%)	0.72 (<0.001)	0.70–0.74
Low-income areas	74 (13%)	Reference category	
Built from 1975–1990			
High-income areas	20 (11%)	1.63 (<0.001)	1.60–1.66
Middle-income areas	102 (55%)	1.52 (<0.001)	1.47–1.59
Middle/low-income areas	42 (23%)	0.66 (<0.001)	0.63–0.69
Low-income areas	20 (11%)	Reference category	
Built from 1990–2000			
High-income areas	105 (11%)	2.21 (<0.001)	2.18–2.24
Middle-income areas	347 (36%)	1.73 (<0.001)	1.71–1.75
Middle/low-income areas	357 (37%)	0.67 (<0.001)	0.65–0.68
Low-income areas	147 (16%)	Reference category	
Built from 2000–2014			
High income areas	124 (28%)	2.20 (<0.001)	2.16–2.24
Middle income areas	103 (24%)	1.93 (<0.001)	1.90–1.96
Middle/low-income areas	185 (43%)	1.03 (0.409)	0.99–1.05
Low-income areas	22 (5%)	Reference category	
Population count		0.85 (<0.001)	0.71–0.93

Table 1A
Comparison of the demographics, water storage capacity, security of tenure, type of toilet facility and durability of housing structure among the utility's residential classes

Parameter	High-income areas (n = 60)	Middle-income areas (n = 170)	Middle/low-income areas (n = 161)	Low-income areas (n = 746)
Average number of people per room in the household	1	1	2	3
Use of a storage tank with a capacity of more than 100 L	46 (77%)	131 (77%)	103 (64%)	271 (36%)
Security of tenure	51 (85%)	126 (74%)	94 (58%)	357 (48%)
Type of toilet facility				
- Flush toilet	54 (90%)	143 (84%)	83 (52%)	257 (34%)
- Pit latrine (individual)	6 (10%)	12 (7%)	13 (8%)	114 (15%)
- Pit latrine (shared)	0 (0%)	15 (9%)	63 (39%)	368 (49%)
- Flying toilet	0 (0%)	0 (0%)	1 (1%)	7 (1%)
Durability of housing structure				
- Permanent	56 (93%)	151 (89%)	111 (69%)	336 (45%)
- Semi-permanent	4 (7%)	19 (11%)	50 (31%)	410 (55%)

4. Discussion

Rapid urbanisation in developing countries in the absence of significant infrastructure growth threatens access to basic amenities including safe drinking water and adequate housing. In this study, we have reported an annual population growth rate of more than 4% between 2008 and 2018 and nearly three times increase in the total population of Nairobi between 1985 and 2008. Based on socio-economic status, the largest increase in population was observed in low-income residential areas and smallest increase in the high-income residential areas. In the last 50 years, only one new dam (commissioned in 1994) has been developed to improve supply of water to Nairobi. We reported large losses with non-revenue water accounting for nearly a third of all water distributed from the water service-reservoirs; an amount more than twice the number of litres required for all residents to access sufficient water. Our study showed residents living in high-income areas were up to six times more likely to have sufficient water compared to residents in low-income areas, highlighting socio-economic inequalities in access to safe drinking water. Additionally, newer neighbourhoods, older neighbourhoods in high- and middle-income areas and less densely populated areas were more likely to enjoy water sufficiency.

Similar high urbanisation rates as observed in Nairobi have been reported in multiple cities in the African region (United Nations, 2018). The observation of most urban residents living in middle/low and low-income areas has been reported elsewhere, with the 2018 World Bank statistics reporting 54% of the urban population in sub-Saharan Africa to be residing in low-income areas (World Bank, 2018). The slow rate of growth in water infrastructure compared to population growth has also been reported in other cities in developing countries, which is mainly attributed to inadequate investment in water infrastructure (Mcdonald et al., 2014).

Whilst there have been several studies of spatio-temporal patterns of urban water distribution in developed countries (Donkor et al., 2014; House-Peters & Chang, 2011), such studies are rare in sub-Saharan Africa. Our study is thus one of a small number of studies that have looked at spatio-temporal urban water distributions. The key findings of our study on socio economic inequalities in water access where residents of high and middle income areas access water through inhouse piped connection while middle/low and low income areas access the resource through shared tap at yard and water kiosks respectively have been reported in other studies conducted in Dar Es Salaam (Dill & Crow, 2014), Nairobi (Dill & Crow, 2014; Dos Santos et al., 2017) and Indian cities (Sidhwani, 2015).

To ensure equitable distribution of water, NCWSC implements a water rationing program. Despite a higher number of hours of water supply per week for middle/low and low-income areas compared to the high- and middle-income areas, low-income areas had higher levels of water insufficiency compared to high-income areas. These differences in water consumption may be explained by the mode of water access, water storage practices and the per unit cost of water. A previous study has reported residents with inhouse piped water connections to own larger water storage tanks that ensure continuous water supply (Cobacho et al., 2008). In Ghana, owners of water kiosks in low income areas retailed water at a cost higher than the price recommended by the utility company, resulting in the residents paying 9–13 times more on water, spending up to 20% of their daily wages (Monney et al., 2013). The cost of vended water in Nairobi has been reported to be $4.73 per thousand litres (Mitlin et al., 2019), more than double what is paid by households with direct water connection to their houses or shared taps in the yard/compound.

Non-revenue water has been estimated to account for 35% of the water distributed in developing countries (González-Gómez et al., 2011). The drivers for this high non-revenue water include high population density, using pumps to increase water pressure through the distribution network, intermittent water supply patterns and distribution to an increasing urban population among others (van den Berg, 2015). In our study, nearly a third of the water distributed was non-revenue water. This loss was more than twice (1.5 billion litres) the monthly amount of water required to ensure all the residential areas had a continuous, sufficient water consumption. Renovating the piped network and planning for water supply infrastructure are some of the main strategies recommended to minimise these losses (van den Berg, 2015). A pilot study conducted in a low income area in Nairobi to assess the impact of citizen engineering using mobile solutions to detect, report and repair water leaks outlined the potential of these technological solutions to reduce water losses by half (Heland et al., 2015). Similarly, Colombia was able to reduce non-revenue water loss by 7% through identifying and replacing the appropriate pipes in the water distribution network that contributed to major leaks in the system (Saldarriaga et al., 2010).

Water is a basic human right and every city should make provision of water that is reliable, safe, and affordable. The African Union Agenda 2063 and the 2030 United Nations Sustainable Development Goals aim to reduce the number of people without adequate water supply (African Union, 2015; United Nations, 2015). By 2030, Nairobi City will be estimated to have over 7 million people (Mcdonald et al., 2014), indicating the need for improvement in the water distribution in residential areas, especially the group at risk. We found notable differences in water distribution between old and newer neighbourhoods and the interaction between neighbourhood age and residence type in Nairobi. Previous studies have reported inequalities in both housing and water distribution, which is driven by prioritisation of high and middle income areas during housing and infrastructure development and poor provision of piped water services in emerging poor neighbourhoods. (Blomkvist & Nilsson, 2017; Kyessi, 2005; Tusting et al., 2019; Watson, 2014).

Previous studies have reported governments as unwilling to provide water to these low-income areas, given the potential to legitimise residents' land tenure by providing services in such unplanned settlements (UN-Habitat, 2013). As having a piped water network might prove difficult in the short term, water kiosks, public taps, and number of days of water provision can be increased for the residents at risk to have relatively more water access. NCWSC has a pilot project where they are installing water dispensing systems in the low-income areas with the aim of improving the accessibility of water and making the commodity more affordable as demonstrated in Luanda, Angola (Maryati & Humaira, 2015).

There were several limitations to this study. The residential area classification and neighbourhood age was derived from the built environment, potentially omitting socio-economic conditions experienced by their residents while also excluding residential areas which were not in the water distribution grid. This problem has been highlighted in a study in both Kenya and Ghana showing the performance indicators used by water distribution companies may be insufficient to evaluate a population's access to safe water (Bellaubi & Visscher, 2014). However, since the data from the utility company were disaggregated spatially, instead of aggregated to the entire supply area, this addressed at least one related concern over the limitations of utility data. Another study limitation was the use of data on the 1985 population counts and population density from the NCWSC which was based on estimates calculated by the utility company using the 1979 national census and the average annual growth rate per residential category. In this study, we did not consider possible intra-itinerary variation, which may have led to the ecological fallacy problem, whereby results from data collected and analysed at a group level are assumed to apply to associations at the individual level (Sedgwick, 2015). Although we have used the 1500 L per month amount to determine water sufficiency levels, the water supplied may have been used for both domestic and economic purposes leading to an overestimate of the proportion of population with sufficient water consumption. There are reports of economic activities in residential settings that rely on household water connections or water from the kiosks (Adank et al., 2012; Duran et al., 2004, pp. 16–21). There is however no widely accepted criterion that covers both domestic and economic uses of water in residential areas, a possible area of research to improve estimates of accessibility to safe drinking water for city residents. Data on shared connection types in itineraries and the extent to which residents accessed alternative safe sources of water in the absence of piped water was unavailable to account for in the analysis. We assumed the water connection type and water distribution programmes from the utility company matched well with the actual water connection types and distribution in the different residential area categories in the supply area respectively. In the absence of available small area statistics from the 2009 or 2019 Kenyan population censuses, we were only able to include three covariates in our spatio-temporal analysis of water sufficiency. However, comparison with socio-economic data from the KSCBS suggested that the utility's residential classification was a reasonable proxy for other socio-economic measures such as security of land tenure and durable housing.

5. Conclusion

From this study, we argue that equity in water distribution, from the mode of access, quantity, to infrastructure development should be prioritised to ensure improved safe water sufficiency for Nairobi. To actualise this, three things are critical: data, infrastructure investments and governance. Data on water supply and consumption is key in assessing the gaps in the water distribution process and to ensure sustainability in water sufficiency. Previously, accessibility of government data has been difficult in African countries where the data has been incomplete or manually stored. However, governments have been working towards ensuring their data is accessible, electronically stored, complete and consistent (United Nations Economic Commission for Africa, 2017) which enables research and future planning.

Improving water sufficiency will require the right investments from the national and international government. Growth in city population should be accompanied by investments in infrastructure to support provision of safe water to the population, including proper funding of water utility companies to enhance their performance (Mcdonald et al., 2014; van den Berg & Danilenko, 2017). The investments of water sufficiency should be categorised based on residential category and neighbourhood age, with focus on the groups at risk.

Finally, good governance that aims to minimise water losses and socio-inequalities is required. There should be deliberate prioritisation of water supply and infrastructure development in low-income areas, both in newer and older neighbourhoods, and densely populated areas, reduction in the non-revenue water and making safe water accessible and affordable to all. These are critical towards achieving the Sustainable Development Goal 6 of clean water and sanitation for all.

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CRediT authorship contribution statement

Nyamai Mutono: Conceptualization, Formal analysis, Investigation, Visualization, Writing – original draft. **Jim Wright:** Conceptualization, Methodology, Validation, Supervision, Data curation, Writing – review & editing. **Henry Mutembei:** Writing – review & editing. **S.M. Thumbi:** Conceptualization, Methodology, Supervision, Resources, Writing – review & editing.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.habitatint.2021.102476.

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