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An examination of water, sanitation, and hygiene (WASH) accessibility and opportunity in urban informal settlements during the COVID-19 pandemic: Evidence from Nairobi, Kenya

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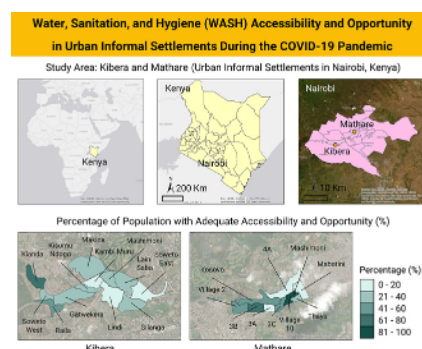[c] Map Kibera Trust, Kenya
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HIGHLIGHTS

- We examined WASH facility accessibility during the COVID-19 pandemic.
- We focused on two urban informal settlements (Kibera and Mathare) in Nairobi, Kenya.
- 77.4% of people living in Kibera have limited WASH accessibility or opportunity.
- 60.6% of people living in Mathare have limited WASH accessibility or opportunity.
- There is a clear geographic pattern in WASH accessibility and opportunity.

GRAPHICAL ABSTRACT

ARTICLE INFO

ABSTRACT

This research examines water, sanitation, and hygiene (WASH) accessibility and opportunity in Kibera and Mathare during the COVID-19 pandemic in 2021. Kibera and Mathare are two of the largest urban informal settlements in Nairobi (the capital city of Kenya) as well as Sub-Saharan Africa. Accessibility indicates how easily a person can reach WASH facilities from their home by walking. Opportunity represents how many WASH options a person has near their home. We utilize the data on water and toilet facilities collected by GroundTruth Initiative in partnership with Map Kibera Trust (local community partners) between February and April 2021 – amid the COVID-19 pandemic. By conducting quantitative geospatial analysis, we illustrate WASH accessibility and related issues that were not evident in previous studies: (1) 77.4% of people living in Kibera have limited WASH facility accessibility or opportunity; (2) 60.6% of people living in Mathare have limited WASH facility accessibility or opportunity; (3) there is a clear geographic pattern in WASH facility accessibility and opportunity; and (4) overall accessibility and opportunity is better in Mathare than in Kibera. This study is one of the first studies to examine WASH accessibility and opportunity in urban informal settlements during the COVID-19 pandemic by utilizing the current data and quantitative geospatial methods. Based on the results, we discuss important public health policy implications for people living in urban informal settlements to improve their WASH facility accessibility and opportunity during the COVID-19 pandemic.

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1. Introduction

Since December 2019, the COVID-19 pandemic has been a major global public health issue. As of the end of December 2021, there are approximately 275 million confirmed cases of COVID-19 and 5.4 million deaths (World Health Organization, 2021). People are strongly recommended to properly practice personal hygiene, such as washing hands often with soap, to reduce the spread of the virus (World Health Organization, 2020). Promoting people's accessibility to water, sanitation, and hygiene (WASH) facilities is important in reducing the spread of viruses and eventually mitigating the COVID-19 pandemic (Donde et al., 2021; Stoler et al., 2020).

Enhancing accessibility to WASH facilities during the COVID-19 pandemic is challenging for countries in Sub-Saharan Africa, where limited accessibility has long been a serious public health issue (Amegah, 2020; Dos Santos et al., 2017; World Health Organization and United Nations Children's Fund (UNICEF), 2017). For example, in 2015, about 42% of people living in Sub-Saharan Africa had limited access to safely managed drinking water services, which is higher than the global percentage (12%) (World Health Organization and United Nations Children's Fund (UNICEF), 2017). Approximately 72% of people living in Sub-Saharan Africa had limited access to safely managed sanitation services, which is higher than the global percentage (32%) (World Health Organization and United Nations Children's Fund (UNICEF), 2017). Low WASH accessibility indicates that people living in these countries cannot properly practice personal hygiene, which may lead to ineffective control of the COVID-19 pandemic. Due to low vaccination rates in Sub-Saharan Africa (as of December 2021), practicing personal hygiene remains one of the most important public health measures to mitigate the COVID-19 pandemic (Tatar et al., 2021; Mathieu et al., 2021).

Many public health researchers have investigated people's accessibility to WASH facilities during the COVID-19 pandemic, focusing on Sub-Saharan African countries (e.g., Anim and Ofori-Asenso, 2020; Kanyangarara et al., 2021; Ogunbode et al., 2021; Okoi and Bwawa, 2020). For example, by utilizing the 2015–2018 Demographic and Health Surveys (DHS) data of 16 countries in Sub-Saharan Africa, Jiwani and Antiporta (2020) observed inequality in access to water and soap on the basis of geography (urban vs. rural areas) and economic status (poor vs. rich people). By utilizing the same dataset (DHS) for 25 countries in Sub-Saharan Africa, Ekumah et al. (2020) estimated that about half of their sampled households did not have access to basic needs of life, including water, sanitation, and food storage facilities.

Although these studies provide a useful foundation for understanding issues of WASH accessibility during the COVID-19 pandemic in Sub-Saharan African countries, there remain two critical limitations.

First, many previous studies analyzed data that were collected before the COVID-19 pandemic (e.g., Ekumah et al., 2020; Jiwani and Antiporta, 2020). The data used in these studies may not adequately capture the most accurate and detailed picture of WASH accessibility during the COVID-19 pandemic. Due to lockdown or quarantine policies, water supply is disrupted, and water demand increases because of people staying in their homes for longer periods of time (Calder et al., 2021). This suggests that people's access to WASH facilities is interrupted during the COVID-19 pandemic. Utilizing data collected before the COVID-19 pandemic does not reflect the most recent situation of how people access WASH facilities during the COVID-19 pandemic. Moreover, they largely focused on country-scale observations, such as comparing WASH accessibility between two countries, which does not illustrate a detailed micro-scale (e.g., neighborhood, city) picture of WASH accessibility during the COVID-19 pandemic.

Second, many previous studies on WASH accessibility during the COVID-19 pandemic have overlooked urban informal settlements as a study area. Because of a lack of proper urban infrastructure planning and management, people living in urban informal settlements have poor accessibility to WASH facilities compared to people living in formal settlements (e.g., Kamau and Njiru, 2018; Lewis et al., 2018; Mels et al., 2009; Zerbo et al., 2020). People living in informal settlements are not able to properly practice personal hygiene due to their limited access to WASH facilities (Corburn et al., 2020; Ilesanmi et al., 2020; Parikh et al., 2020; Stoler et al., 2020), which can lead to serious public health concerns in urban informal settlements during the COVID-19 pandemic. Therefore, it is critical to examine WASH accessibility and related issues of people living in urban informal settlements. Apart from a few exceptions (e.g., Taylor et al., 2021), WASH accessibility in urban informal settlements has not been investigated empirically.

To fill these significant gaps, this research investigates WASH facility accessibility in two urban informal settlements: Kibera and Mathare in Nairobi, Kenya. Regarding the WASH facility, we particularly focus on water facilities and sanitation (especially toilets), which are important during the pandemic. We use the current WASH facility data related to their operational and service aspects. The data were collected during the COVID-19 pandemic. Water facilities include various types of facilities, such as piped water, water kiosk, water tank, and water tower. Toilets include ablution block, English style, hanging toilet, pit latrine, and trench toilet. We also utilize data from surveys on people's experiences of using WASH facilities. These datasets were collected by GroundTruth Initiative in partnership with Map Kibera Trust (local community partners) during the pandemic (February–April 2021).

By conducting quantitative geospatial analysis, we aim at addressing the following questions. **RQ1**. What are the water facility accessibility and opportunity of the study areas? Accessibility indicates how easily a person can reach WASH facilities (e.g., water facilities, toilets) from their home by walking; opportunity represents how many WASH facility options a person has near their home. **RQ2**. What are the toilet accessibility and opportunity of the study area? **RQ3**. What is the overall WASH facility accessibility and opportunity of the study area? Based on the results, we further discuss important public health policy implications.
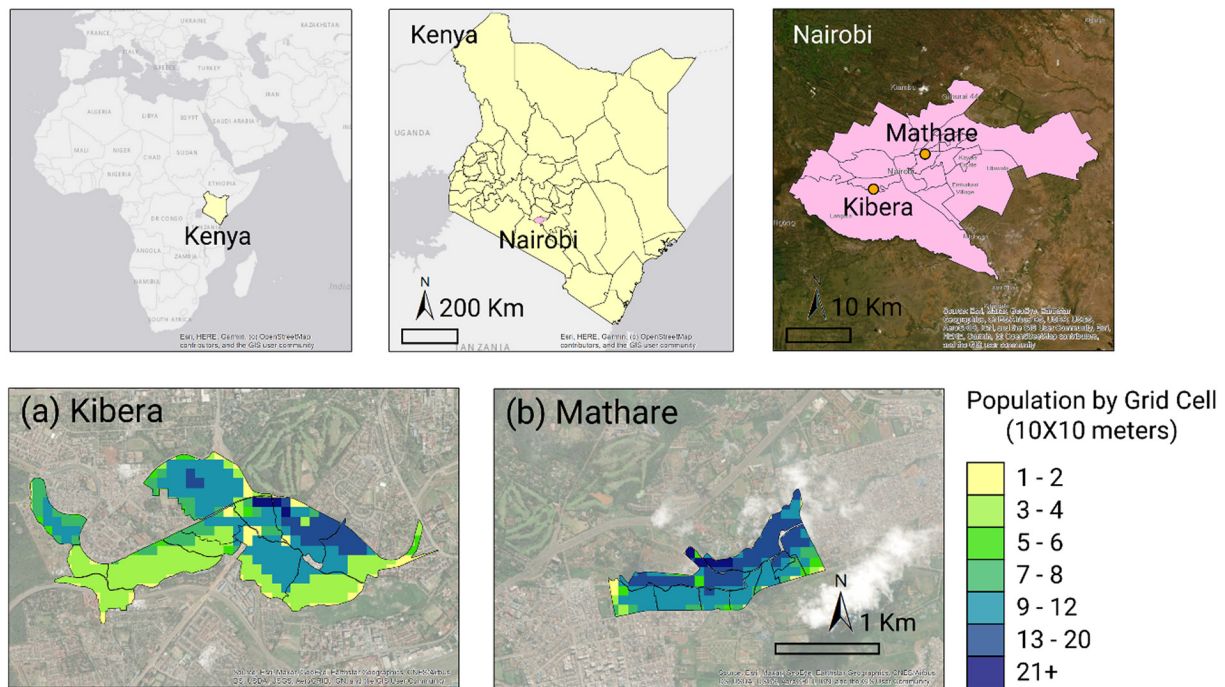
2. Study area and data

2.1. Study area

Our study area consists of two urban informal settlements – Kibera (central part of Nairobi) and Mathare (approximately 10 km northeast of Kibera) – in Nairobi, the capital city of Kenya (Fig. 1).

Kibera and Mathare are two of the largest urban informal settlements in Nairobi as well as Sub-Saharan Africa. We selected Kibera and Mathare as our study area because WASH and general public health issues in Kibera and Mathare were critical even before the COVID-19 pandemic (e.g., Corburn and Hildebrand, 2015; Corburn and Karanja, 2014; Darkey and Kariuki, 2013; Edwards et al., 2015; Mutisya and Yarime, 2011). We focused on 12 villages (administrative boundary) in Kibera and 10 villages in Mathare. We focused on villages that largely consist of informal settlements. For example, Ayany, Karanja, and Olympic villages in Kibera and Mathare Village 1 in Mathare were excluded because they have relatively lower percentages of informal settlement areas.

According to the population data estimation by WorldPop, there were 136,806 people living in Kibera and 85,522 living in Mathare in 2020 (Bondarenko et al., 2020). Because of the intrinsic informal characteristics of the study area, it is difficult to accurately estimate the boundary and population of Kibera and Mathare. Thus, one should bear in mind that our population estimation (obtained from WorldPop 2020) and the actual population may differ due to these data limitations. As of the end of December 2021, the cumulative confirmed COVID-19 cases per million people in Kenya is 4796, which is lower than that of Africa as a whole (6688) but higher than adjacent countries, such as Ethiopia (3193), Uganda (2739), Somalia (1416), South Sudan (1169), and Tanzania (431) (Our World in Data, 2021). Moreover, recent epidemiological studies focusing on Nairobi and Kibera found that more than a third of people were exposed to SARS-CoV-2, indicating that spread of the virus was severe in our study area (e.g., Ngere et al., 2021).

Fig. 1. Population distribution of the (a) Kibera and (b) Mathare urban informal settlements. (Note: Our population estimation that was obtained from WorldPop 2020 [Bondarenko et al., 2020] and the actual population may differ due to the intrinsic informal characteristics of the study area.)

2.2. Data

2.2.1. Population data

We utilized the WorldPop 2020 Kenya population data (Bondarenko et al., 2020). The population is estimated at a grid cell of 100 by 100 m. WorldPop utilizes satellite images, available census data, and machine learning methods to estimate the population of each 100 by 100 m grid cell (Bondarenko et al., 2020). Considering that the accurate fine-scale census-based population data of urban informal settlements is not widely available for the public and researchers, WorldPop population data are particularly useful to estimate the population of urban informal settlements (e.g., Lloyd et al., 2017; Ren et al., 2020; Tatem, 2017). However, one caveat is that WorldPop population data are not necessarily the same as the actual population of the study area, especially when the study area is an informal settlement. Because of the intrinsic informal characteristics of the study area, one should bear in mind that WorldPop population data has an important limitation in accurately estimating population (e.g., Hagen, 2021). We adopted a grid cell of 10 by 10 m as a unit of analysis because grid cells of 100 by 100 m cannot accurately capture the detailed boundaries of Kibera and Mathare. Assuming that the spatial distribution of population is homogeneous within each 100 by 100 m grid cell, we divided the population estimation by 100 to estimate the population at a grid cell of 10 by 10 m that belongs to the 100 by 100 m grid cell.

2.2.2. Map Kibera Trust Cities' COVID Mitigation Mapping (C2M2) data

We utilized a dataset collected by GroundTruth Initiative in partnership with Map Kibera Trust, a nonprofit organization in Nairobi, Kenya. The data were collected by local agents of Map Kibera Trust between February and April 2021. Data collectors physically visited the study area and collected information on WASH facilities while following safety measures, such as practicing social distancing and wearing a mask. The data are open to the public through the OpenStreetMap. The data collection process was supported by the Cities' COVID Mitigation Mapping (C2M2) Program of the U.S. Department of State (MapGive, 2021). As part of the MapGive initiative directed by the U.S. Department of State's Humanitarian Information Unit, the C2M2 Program aims at building local capacity to utilize open-source geospatial technologies, strengthening international partnerships,

and creating new information to inform data-driven decision making for policies that address COVID-19s second-order impacts (Laituri et al., 2021; MapGive, 2021).

We focused on the following three topics from the dataset. First, we utilized survey items related to people's opinions on WASH services (particularly water and toilet) during the COVID-19 pandemic. The survey items include: (1) whether people face any difficulty in accessing enough water, (2) whether their water service is reliable, (3) whether they require more water than usual, (4) whether their toilet is private or in-compound, (5) whether they are satisfied with their toilet service, and (6) why they are not satisfied with their toilet service. The survey dataset consists of 647 people's responses (Kibera: 323; Mathare: 324) that have been completely anonymized. The survey did not ask for any personal or sensitive information, such as home location, name, and household income. Although the survey participants were relatively evenly selected across the entire study area, they were chosen through a convenience sampling process because the study area consists of informal settlements.

Second, we utilized data related to water facilities and toilets (Fig. 2). The data consists of detailed attributes of water facilities and toilets in Kibera and Mathare, including their geographic location (longitude and latitude), reliability (whether a facility is operational), and price policy. The attributes of each facility were observed and recorded when Map Kibera Trust agents physically visited each facility. Although there are 835 water facilities (e.g., piped water, water kiosk, water tank, and water tower) in the study area, we focused on 257 adequate water facilities (Kibera: 158; Mathare: 99) that are reliable (i.e., frequently operational) and charge reasonable prices (less than 5 Kenyan shillings per 20 l). The low cost of water is important for informal settlements because of the potential impacts of water cartels (Reuter, 2021). Water cartels may charge a high price for water, which may eventually restrict people from accessing water services during the COVID-19 pandemic. Fig. 3 presents photos of selected adequate water facilities. Note that the Map Kibera Trust data do not have information on water quality (e.g., chemistry, biology, and nutrients). Our study focuses on the operational or service aspects of water facilities.

Third, there are 837 toilets (e.g., ablution block, English style, hanging toilet, pit latrine, and trench toilet) in the study area, but we focused on 210 adequate toilets (Kibera: 143; Mathare: 67) that are reliable (i.e., frequently
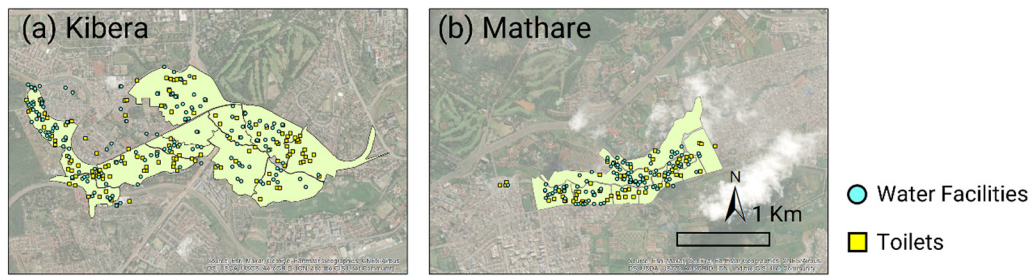
Fig. 2. (a) 158 adequate water facilities and 143 adequate toilets in Kibera; (b) 99 adequate water facilities and 67 adequate toilets in Mathare.

Fig. 3. Photos of selected adequate water facilities in the study area (Note: [a]: water tank; [b]: piped water; [c]: piped tap).

operational), are of good quality (regarding the cleanness and maintenance), and have a handwashing facility. These attributes are important as people can properly practice hygiene and sanitation after using toilets. For example, some toilets do not frequently operate so that people cannot access the facilities when they want, which may impede people from practicing personal hygiene properly. Fig. 4 presents photos of selected adequate toilets.

3. Methods

This section describes the method of our study. Fig. 5 illustrates the overall method of our study. We obtained descriptive statistics of six survey items related to people's opinions on water facilities and toilets during the COVID-19 pandemic (Fig. 5[a]). The survey items include: (1) whether people face any difficulty in accessing enough water, (2) whether their water service is reliable, (3) whether they require more water than usual, (4) whether their toilet is private or in-compound, (5) whether they are satisfied with their toilet service, and (6) why they are not satisfied with their toilet service.

Next, we conducted quantitative geospatial analyses. Specifically, we measured distances to adequate WASH facilities (water facilities and toilets) for each grid cell (10 by 10 m) in the study area (Fig. 5[b]). Recall that adequate water facilities are reliable (i.e., frequently operational) and charge reasonable prices (less than 5 Kenyan shillings per 20 l). Adequate toilets are reliable (i.e., frequently operational), are of good quality, and have a handwashing facility (see Section 2.2.2 for more details). For each grid cell, we measured a distance from the centroid to the nearest adequate water facility (or toilet). A lower value of distance indicates higher accessibility, as accessibility indicates how easily a person can reach adequate WASH facilities from their home by walking (e.g., Kim and Lee, 2019; Lee and Miller, 2020). Moreover, we define water facilities (or toilets) opportunity as the number of adequate water facilities (or toilets) within 100 m of walking distance from the centroid of each grid cell (Fig. 5[c]). Opportunity represents how many WASH facility options a person has from their home location (e.g., Kwan, 1998). A high value of opportunity indicates that a person has many WASH facility options that can be reached within 100 m of walking distance.
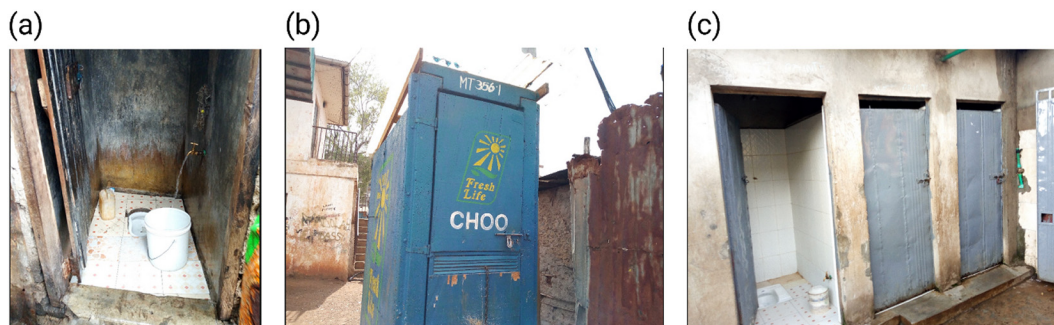

Fig. 4. Photos of selected adequate toilets that are of good quality. (Note: [a]: trench toilet; [b]: pit latrine; [c]: ablution block).
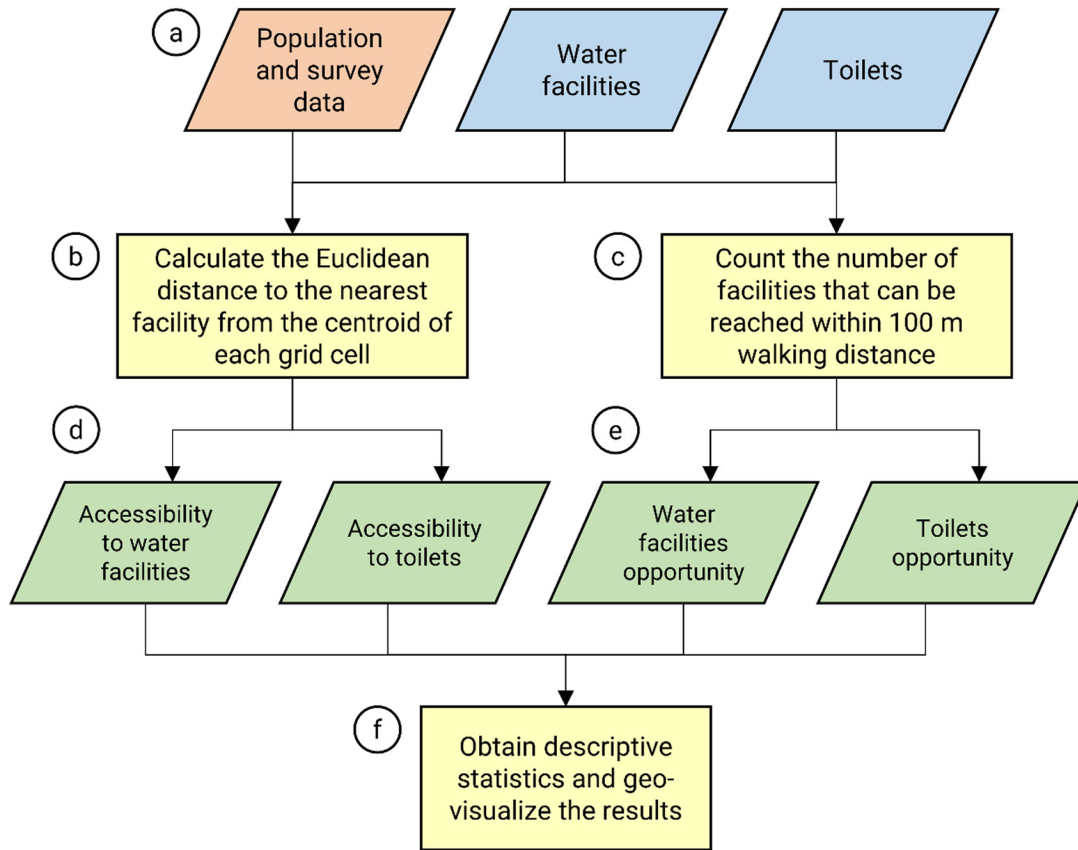
Fig. 5. An overview of the research method.

We selected 100 m for the threshold of limited accessibility to water facilities and toilets, based on local knowledge and international guidelines (e.g., World Health Organization, 2003, p.3). Note that although it would be ideal to use a pedestrian network-based approach to measure walking distance, we used Euclidean distance because detailed pedestrian network data is not available for our study area. Since small-sized residential lots are densely located in the study area, we assumed that a travel distance obtained from the Euclidean approach would not be substantially different from that obtained from the pedestrian network-based approach (e.g., Davis et al., 2020; Nesbitt et al., 2014; Shores et al., 2019).

As a result, for each grid cell, we utilized two WASH accessibility measurements (Fig. 5[d]): (1) accessibility to water facilities and (2) accessibility to toilets. We also utilized two WASH opportunity measurements (Fig. 5[e]): (1) water facility opportunity and (2) toilet opportunity. We obtained descriptive statistics of the accessibility and opportunity measures and produced maps that visualize the accessibility and opportunity of each grid cell of Kibera and Mathare to understand the geographic pattern of WASH accessibility and opportunity (Fig. 5[f]).

4. Results

4.1. Results based on the survey responses

This subsection illustrates the survey results of 647 people (Kibera: 323; Mathare: 324) living in the study area (Table 1).

We focused on three survey items related to water accessibility during the COVID-19 pandemic. First, nearly 80% of people living in Kibera and Mathare have had difficulty accessing enough water during the pandemic (Water-1). Second, roughly 80% of people living in the Kibera and Mathare neighborhoods reported that their water operation is unreliable (Water-2). Third, 72% of people living in Kibera and 91% of people living in Mathare

reported that they required more water during the COVID-19 pandemic than usual (Water-3).

We examined three survey items related to toilet accessibility. First, 4% of people living in Kibera use private in-home toilets, whereas 1% of people living in Mathare do (Toilet-1). 53% of people living in Kibera use in-compound toilets, whereas 56% of people living in Mathare do (Toilet-1). Second, 19% of people living in Kibera and 25% of people living in Mathare reported that they are not satisfied with their toilet service (Toilet-2). Third, approximately 60% of people living in Kibera and Mathare who are not satisfied with their toilet service reported that poor maintenance of the toilet (especially cleanliness) is one of the most important reasons for not being satisfied (Toilet-3).

Table 1
Results of the survey responses.

Item	Description	Response	Kibera	Mathare
Water-1	Did you face any difficulty in accessing enough water?	Yes	78.5%	77.9%
		No	21.5%	22.1%
Water-2	Was the water service reliable?	Unreliable	78.5%	82.1%
		Reliable	21.5%	17.9%
Water-3	Did you require more water than usual?	Yes	72.4%	91.0%
		No	27.6%	9.0%
Toilet-1	What was the type of the toilet?	Private	4.3%	0.9%
		In-compound	53.3%	55.6%
		Public	42.4%	43.5%
Toilet-2	Were you satisfied with the toilet service?	Not satisfied	18.6%	25.1%
		Satisfied	57.3%	46.1%
		Very satisfied	24.1%	28.8%
Toilet-3	Why were not you satisfied with their toilet service?	Poor maintenance	56.7%	59.3%
		No water for flushing	26.7%	17.3%
		Safety	13.3%	16.0%
		Others	3.3%	7.4%

Table 2

Descriptive statistics of water facility accessibility and opportunity measures.

Informal settlements	Descriptive statistics	Accessibility (distance to the nearest adequate water facility)	Opportunity (number of adequate water facilities within 100 m)
Kibera	Average	95.5 m	1.65
(n = 19491)	S.D.	87.9	1.91
	Min	0.2 m	0.00
	Max	803.9 m	16.00
	1st Quartile	44.8 m	0.00
	3rd Quartile	117.4 m	2.00
Mathare	Average	86.4 m	2.86
(n = 7603)	S.D.	84.4	2.92
	Min	1.1 m	0.00
	Max	573.2 m	16.00
	1st Quartile	34.1 m	0.00
	3rd Quartile	106.3 m	4.00

Notes: n denotes the number of grid cells (10 by 10 m) in each neighborhood.

Overall, given the critical role of accessibility to WASH facilities in reducing the spread of viruses (Amegah, 2020; Corburn et al., 2020), our survey results reveal the need to investigate accessibility to WASH facilities in urban informal settlements.

4.2. Results on water facility accessibility and opportunity

This subsection illustrates results on water facility accessibility and opportunity. Table 2 illustrates the descriptive statistics of water facility accessibility and opportunity measures.

For water accessibility, the average distance in Kibera is 96 m, while that in Mathare is 86 m. Accessibility is measured as a distance, so a higher distance indicates lower accessibility. This indicates that water accessibility, on average, is better in Mathare than in Kibera. However, the average distance in both Kibera and Mathare is close to 100 m, which is a threshold value of the acceptable distance to water facilities, as we discussed in Section 3. This indicates that both neighborhoods have limited accessibility. In terms of water opportunity, the average opportunity is 1.65 in Kibera and 2.863 in Mathare, indicating that people living in Mathare on average have more water facility options than people living in Kibera. The standard deviations of accessibility and opportunity measures are large, indicating

that there is a huge deviation in water accessibility and opportunity within informal settlements.

We examined the geographic pattern of water facility accessibility and opportunity. Fig. 6(a) and (b) illustrate the distance to the nearest adequate water facility from the centroid of each grid cell (10 by 10 m) in Kibera and Mathare, respectively. The color indicates the distance: Red indicates a long distance (i.e., low accessibility), while yellow indicates a short distance (i.e., high accessibility). Fig. 6(c) and (d) illustrate the number of adequate water facilities within 100 m. The darker blue indicates more opportunities, while the lighter blue indicates fewer opportunities. Boundaries illustrated in the figure indicate the villages' boundaries.
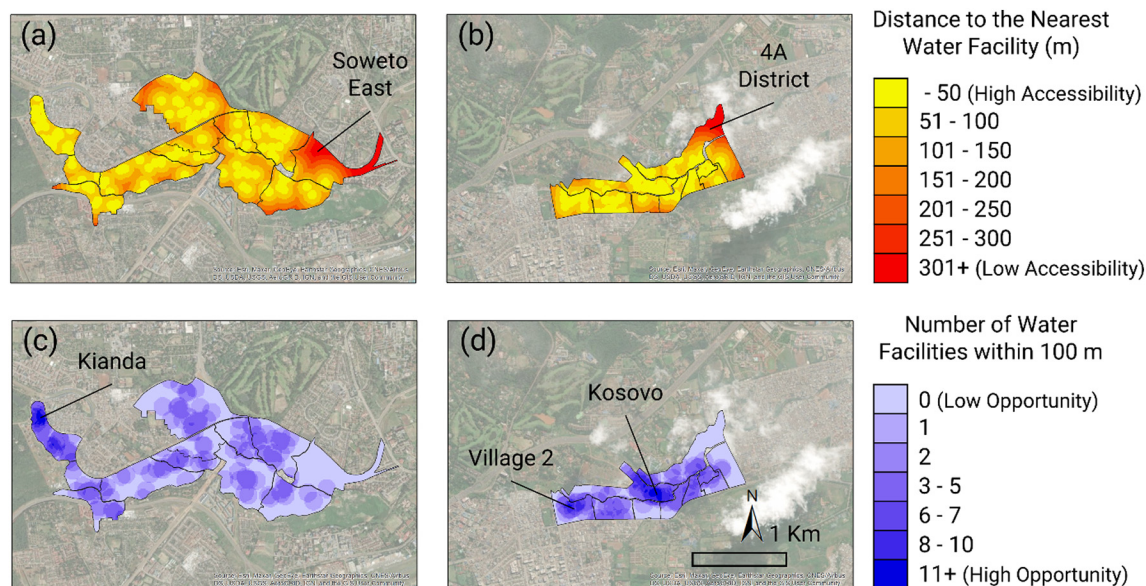
We observed that there is a geographic pattern regarding water facility accessibility and opportunity. First, there is a positive relationship between accessibility and opportunity: areas with higher accessibility have more opportunities. The Spearman correlation test result also reveals that the correlation between water facility accessibility (multiplied by −1) and opportunity is significant in both Kibera (ρ: 0.831, $p < 0.001$) and Mathare (ρ: 0.818, p < 0.001). Second, the Soweto East village in Kibera and the Mabatini and 4A villages in Mathare have lower water accessibility and opportunity than other villages. Third, the Kianda village in Kibera and the Village 2 and Kosovo villages in Mathare clearly have more opportunities for adequate water facilities than other areas. Overall, the results suggest that there is a clear geographic disparity in water accessibility and opportunity in the study area.

4.3. Results on toilet accessibility and opportunity

Table 3 illustrates the descriptive statistics of toilet accessibility and opportunity measures.

For toilet accessibility, the average distance in Kibera is 89 m, while that in Mathare is 93 m. This indicates that toilet accessibility on average is slightly better in Mathare than in Kibera. In terms of toilet opportunity, the average opportunity is 1.565 in Kibera and 1.874 in Mathare, indicating that people living in Mathare, on average, have more toilet options than people living in Kibera. Similar to what we observed with water accessibility and opportunity, note that the standard deviations of toilet accessibility and opportunity measures are large, indicating a huge deviation in toilet accessibility and opportunity within informal settlements.

We examined the geographic pattern of toilet accessibility and opportunity. Fig. 7(a) and (b) illustrate the distance to the nearest adequate toilet

Fig. 6. Accessibility to adequate water facilities in (a) Kibera and (b) Mathare. Water facility opportunity in (c) Kibera and (d) Mathare. (Note: Accessibility indicates how easily a person can reach adequate water facilities from their home by walking. Opportunity represents how many adequate water facility options a person has near their home.)

Table 3
Descriptive statistics of toilet accessibility and opportunity measures.

Informal settlements	Descriptive statistics	Accessibility (distance to the nearest adequate toilets)	Opportunity (number of adequate toilets within 100 m)
Kibera (n = 19491)	Average	89.4 m	1.57
	S.D.	79.9	1.66
	Min	0.2 m	0.00
	Max	801.8 m	10.00
	1st Quartile	44.0 m	0.00
	3rd Quartile	111.7 m	2.00
Mathare (n = 7603)	Average	93.0 m	1.87
	S.D.	78.9	1.92
	Min	0.8 m	0.00
	Max	497.0 m	10.00
	1st Quartile	40.0 m	0.00
	3rd Quartile	116.7 m	3.00

Notes: n denotes the number of grid cells (10 by 10 m) in each neighborhood.

from the centroid of each grid cell (10 by 10 m) in Kibera and Mathare, respectively. Fig. 7(c) and (d) illustrate the number of adequate toilets that can be reached within 100 m. Similar to what we observed with water facilities, we observed that there is a geographic pattern regarding toilet accessibility and opportunity. First, areas with higher toilet accessibility have more toilet opportunities. The Spearman correlation test result also reveals that the correlation between toilet accessibility (multiplied by −1) and opportunity is significant in both Kibera (ρ: 0.823, $p < 0.001$) and Mathare (ρ: 0.826, p < 0.001). Second, the Soweto East village in Kibera and the Mabatini and 4A villages in Mathare have lower toilet accessibility and opportunity than other villages. Third, the Gatwekera and Laini Saba villages in Kibera and the 3B village in Mathare clearly have more opportunities for adequate toilets than other areas.

4.4. Results on overall WASH accessibility and opportunity

Fig. 8 illustrates overall WASH accessibility and opportunity. The overall WASH accessibility (or opportunity) represents the combined assessment of water facility and toilet accessibility (or opportunity). We particularly highlight grid cells whose WASH accessibility and opportunity are both adequate, which is defined as the following: (i) distances to the nearest adequate water facility and toilet are equal to or less than 100 m (indicating

high accessibility) and (ii) the number of adequate water facilities and toilets that can be reached within 100 m is equal to or higher than two (indicating many opportunities). In Fig. 8(a) and (b), green indicates grid cells (10 by 10 m) whose WASH accessibility and opportunity are adequate. Fig. 8(c) and (d) and Table 4 illustrate the percentage of the population with adequate WASH accessibility and opportunity for each village in the study area.
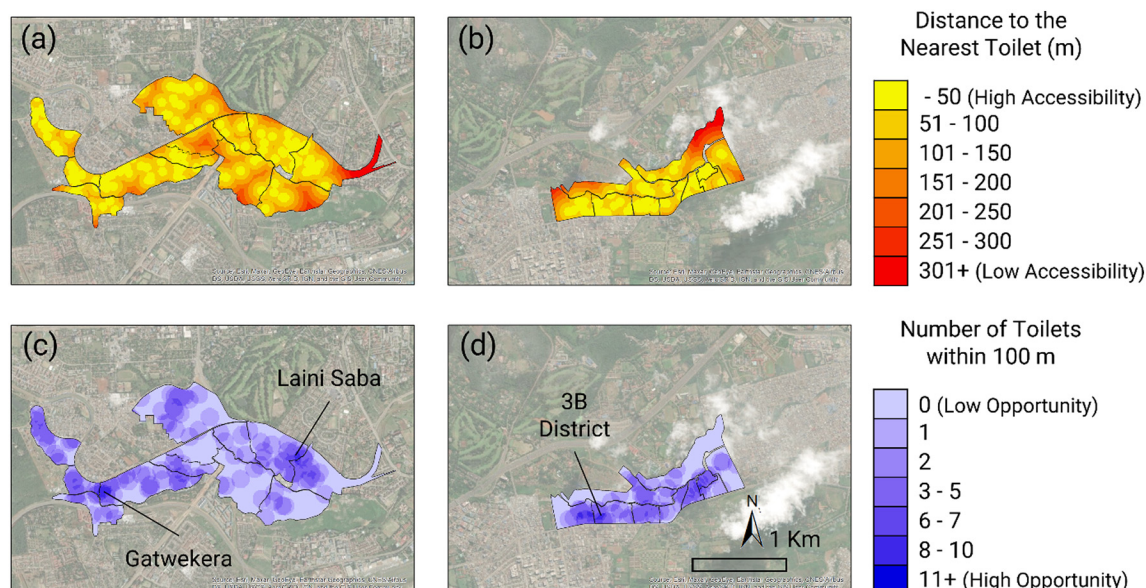
In Kibera, the Kianda and Raila villages are better in the overall WASH accessibility and opportunity than other villages. However, the Kambi Muru, Lindi, and Soweto East villages have poorer WASH accessibility and opportunity. For instance, in the Kambi Muru and Lindi villages, only 3 and 2% of people, respectively, have good WASH accessibility and opportunity. In Soweto East, there are no people with good WASH accessibility and opportunity.

In Mathare, more than 90% of people living in the Mashimoni village and Village 10 have good WASH accessibility and opportunity, but less than 20% of people living in the 3A, 4A, and Mabatini villages have good WASH accessibility and opportunity. When comparing Kibera and Mathare, Kibera has a lower percentage (22.6%) of people with good WASH accessibility and opportunity than Mathare (39.4%). This indicates that people living in Kibera have more limited WASH accessibility and opportunity than people living in Mathare. However, since our population data (obtained from WorldPop) are not necessarily the same as the actual population of the study area, there is a caveat for deriving public policy implications from our findings related to population estimation.
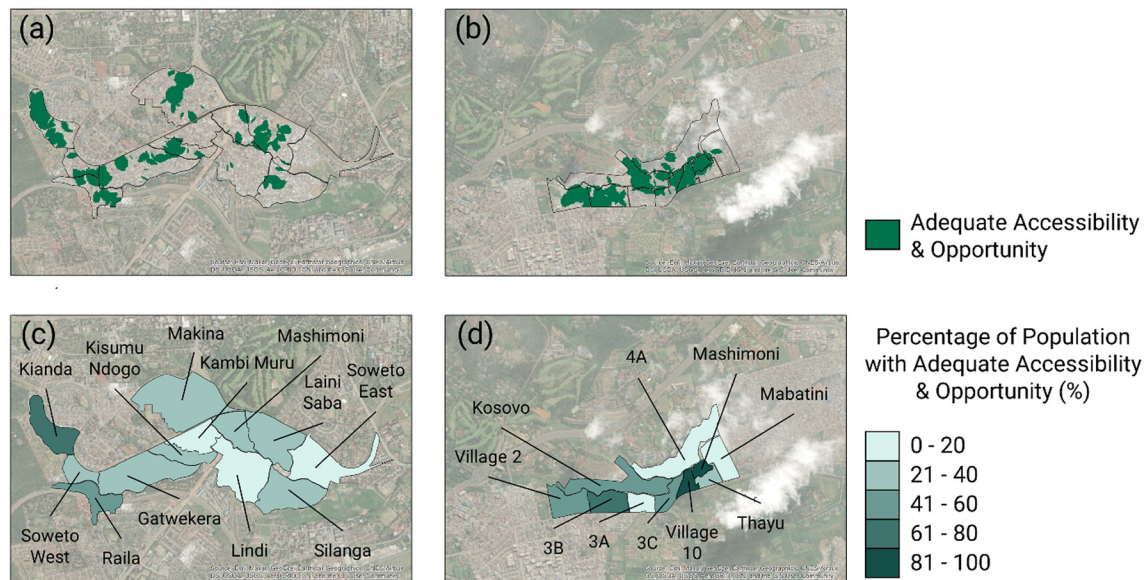
5. Conclusion and discussion

This research examined the WASH facility (water facilities and toilets) accessibility and opportunity in Kibera and Mathare during the COVID-19 pandemic. Kibera and Mathare are urban informal settlements in Nairobi, Kenya. We utilized the current data on water and toilet facilities collected by GroundTruth Initiative in partnership with Map Kibera Trust (local community partners) during the COVID-19 pandemic (February–April 2021). To measure accessibility, we created 10 by 10 m grid cells within the study area and calculated the distance from the centroid of each grid cell to its nearest facility. To measure opportunity, we counted the number of facilities that can be reached within 100 m.

By analyzing people's responses to the survey on their WASH experiences during the COVID-19 pandemic, the results revealed that people

Fig. 7. Accessibility to adequate toilets in (a) Kibera and (b) Mathare. Toilet opportunity in (c) Kibera and (d) Mathare. (Note: Accessibility indicates how easily a person can reach adequate toilets from their home by walking. Opportunity represents how many adequate toilet options a person has near their home.)

Fig. 8. Grid cells (10 by 10 m) with adequate WASH accessibility and opportunity in (a) Kibera and (b) Mathare; Percentage of population with adequate accessibility and opportunity in (c) Kibera and (d) Mathare. Grid cells are considered to have adequate accessibility and opportunity if they meet the following criteria: (i) distances to the nearest adequate water facility and toilet are equal to or less than 100 m (indicating high accessibility) and (ii) the number of adequate water facilities and toilets that can be reached within 100 m is equal to or higher than two (indicating many opportunities).

living in the study area think WASH accessibility was limited during the pandemic: Nearly 80% of people living in Kibera and Mathare have had difficulty accessing enough water during the pandemic. 4% of people living in Kibera use private toilets, whereas 1% of people living in Mathare do. By conducting quantitative geospatial analysis, our results illustrated specific pictures of WASH accessibility and opportunity issues that were not revealed by previous studies. For example, our results revealed that (1) 77.4% of people living in Kibera have limited WASH facility accessibility or opportunity; (2) 60.6% of people living in Mathare have limited WASH facility accessibility or opportunity; (3) there is a geographic pattern in WASH facility accessibility and opportunity; and (4) overall accessibility and opportunity is better in Mathare than in Kibera.

Our study is significant as it is one of the first studies that attempted to examine WASH accessibility and opportunity in urban informal settlements during the COVID-19 pandemic utilizing the most up-to-date data and quantitative geospatial methods. Although our study focuses on two specific urban informal settlements in Nairobi, Kenya, the overall method

and approach presented in our study can be easily applied to other informal settlements in low- and middle-income countries where limited WASH facility accessibility has been a critical public health issue (e.g., Giné-Garriga et al., 2021; Ilesanmi et al., 2020; Parikh et al., 2020; Stoler et al., 2021; Yu et al., 2021).

Another significant aspect of our study is that the results provide important public health policy implications for people living in urban informal settlements to improve their accessibility to WASH facilities during the COVID-19 pandemic. Given that access to WASH facilities plays a critical role in reducing the spread of viruses during the COVID-19 pandemic (Donde et al., 2021; Stoler et al., 2020), limited accessibility may lead to serious public health concerns for people living in urban informal settlements, where personal hygiene was an important public health issue even before the COVID-19 pandemic. Our results call for public health policy attention to improving the WASH facility accessibility of people living in urban informal settlements.

However, there are several limitations that should be addressed by future studies. First, population distribution data obtained from WorldPop might not reflect the actual population of Kibera and Mathare. Because of the intrinsic informal characteristics of urban informal settlements, it is difficult to estimate population distribution accurately (Kanjir et al., 2012; Sartori et al., 2002). Due to limited policy resources, robust and accurate census data might not be available for urban informal settlements and cities in low- and middle-income countries in general. Therefore, future research should actively coordinate with local policymakers to obtain high-quality population data of urban informal settlements, which may eventually benefit from the production of scientific research outcomes and policy recommendations aiming at improving public health.

Moreover, we assumed that people access water facilities and toilets from their home locations. However, even during the COVID-19 pandemic, some people (e.g., essential workers) might travel to non-residential areas where they also need to access WASH facilities (e.g., Kim and Kwan, 2021; Kwan, 2012, 2013). Therefore, future studies should consider population dynamics (i.e., daily activity-travel patterns) to estimate accessibility to WASH facilities more accurately. Lastly, we assumed that people would choose the nearest water facility and toilet. Although this may be a plausible assumption, people's behaviors and preferences might be more complex. For instance, there could be a mismatch between supply and demand that might lead to excessive queues (e.g., Kang et al., 2020; Luo and Wang,

Table 4
Percentage of population with adequate WASH accessibility and opportunity in each village.

Kibera		Mathare	
Village	Percentage (%)	Village	Percentage (%)
Kianda	65.6	Mashimoni	99.4
Raila	49.5	Village 10	92.2
Soweto West	38.2	3B	74.4
Kisumu Ndogo	37.5	Village 2	59.5
Laini Saba	32.0	3C	49.6
Gatwekera	25.9	Kosovo	43.8
Makina	23.9	Thayu	28.2
Mashimoni	21.2	3A	19.7
Silanga	21.2	4A	18.7
Kambi Muru	2.9	Mabatini	11.7
Lindi	2.1	–	–
Soweto East	0.0	–	–

Note: Grid cells are considered to have adequate accessibility and opportunity if they meet the following criteria: (i) distances to the nearest water facility and toilet are equal to or less than 100 m (indicating high accessibility) and (ii) the number of water facilities and toilets that can be reached within 100 m is equal to or higher than two (indicating many opportunities).

2003). Future studies should aim for a more detailed picture of people's behaviors related to WASH facilities.

Furthermore, due to the limitation of pre-pandemic data, we were not able to directly measure how the pandemic changes people's access to WASH facilities. However, we can guess that the COVID-19 pandemic considerably limits people's WASH accessibility from one of our survey results: Approximately 80% of people living in the study area reported that they had difficulty accessing enough water during the pandemic. Thus, future studies can adopt a longitudinal approach to investigate how the pandemic changes the WASH accessibility. The longitudinal approach would also be helpful to examine the effectiveness of existing COVID-19 mitigation policies of Kenya (e.g., the Ministry of Water, Sanitation and Irrigation in collaboration with the Ministry of Housing, Nairobi County, and other development partners) on people's WASH accessibility.

Despite these limitations, our results can significantly assist the public policy decision-makers by suggesting candidate locations where new WASH facilities can be located to improve WASH accessibility and opportunity. For example, our results revealed that overall WASH accessibility and opportunity are limited in the Kambi Muru, Lindi, and Soweto East villages in Kibera and the 3A, 4A, and Mabatini villages in Mathare. Thus, public health policymakers need to focus on improving those areas by providing proper WASH equipment, such as water kiosks and toilets that are reliable, affordable, safe, and clean. Considering the limited policy resources of low- and middle-income countries, where improving public health in urban informal settlements is one of the key urban policy goals (e.g., United Nations Sustainable Development Goals #6: Clean Water and Sanitation), our results are significant as they allow public health policymakers to focus on certain locations that need help the most.

CRediT authorship contribution statement

Junghwan Kim: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Erica Hagen:** Conceptualization, Data curation, Validation, Writing – review & editing. **Zacharia Muindi:** Conceptualization, Data curation, Validation, Writing – review & editing. **Gaston Mbonglou:** Conceptualization, Data curation, Validation, Writing – review & editing. **Melinda Laituri:** Conceptualization, Methodology, Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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