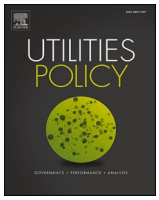
Utilities Policy 96 (2025) 102010

Contents lists available at ScienceDirect

Utilities Policy

journal homepage: www.elsevier.com/locate/jup



Full-length article

The impact of the delegated management model of urban piped service delivery on water quality in Kisumu, Kenya

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ARTICLE INFO

Handling editor: Janice A. Beecher

Keywords:
Impact evaluation
Utility partnerships
Water safety.[1]

ABSTRACT

Delegated management (DMM) is a water service delivery model, whereby micro-operators financially and operationally manage underserved areas of a piped network. This post-hoc evaluation aimed to assess the impact of DMM on water safety. Kiosk and household stored water in DMM and matched control areas were tested for microbiological quality, showing comparable, substantial post-collection contamination. DMM increased household piped connections, reducing the need for household water storage and thereby post-collection contamination. However, DMM kiosk users remain exposed to recontaminated water. DMM remains a viable service delivery model, but other strategies are needed to address post-collection contamination of household stored water.

1. Introduction

In 2022, 2.2 billion people, or 26 % of the world's population, lacked access to safely managed drinking water services, primarily in rural areas and the least developed countries (UNICEF & WHO, 2023). The indicator for monitoring Sustainable Development Goal (SDG) target 6.1, which concerns universal access to safe and affordable drinking water, defines such services as being on-premises, available when needed, and free from contamination (United Nations, 2024). In addition, nearly half (49 %) of the global population may be at significant risk because the quality of their water sources is unknown due to a lack of data (UNICEF & WHO, 2023). Among urban households in Sub-Saharan Africa (SSA), only 53.0 % had access to safely managed water when needed in 2022 (UNICEF/WHO JOINT MONITORING PROGRAM, 2023). The total population in SSA lacking safely managed drinking water increased by 50.5 % from 2000 to 2022 (UNICEF/WHO JOINT MONITORING PROGRAM, 2023). Furthermore, those with piped water access face other challenges, including regular supply disruptions (Bivins et al., 2017). Thus, programmes that ensure households have adequate, affordable, reliable access to safe water are key to delivering SDG6.

Several models exist for improving urban water access, both informal and formal. One such approach is known as the Delegated Management Model (DMM), which involve a formal contract between a water utility and a private individual or group by which the utility delegates operational responsibility for infrastructure and water service delivery within a given urban area (Adams et al., 2019). These small-scale partnerships have been formed in underserved urban neighbourhoods, often characterized by low-income or informal settlements (Njiru, 2004). This model has been utilized in Arusha, Tanzania (Castro and Morel, 2008); Manila, Philippines (Castro and Morel, 2008); Maputo, Mozambique (Matsinhe et al., 2008; Triche et al., 2009); and Ouagadougou, Burkina Faso (dos Santos, 2014). In many implementations, DMM exemplifies a formal partnership between a utility and the community it serves via the establishment of a community liaison committee. By accessing community resources through DMM using this committee structure, the utility mobilizes operational support in low-income areas (LIAs), thus overcoming barriers that prevent such areas from accessing higher levels of services such as household connections.

DMM was intended to improve service coverage and quality, reduce unaccounted-for water by addressing illegal connections, tariff non-payment, and localized pipe breakages; enhance access to safe water; and provide income-generating opportunities for slum dwellers (World Bank, 2009). Many Kenyan water utilities have implemented DMM,

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https://doi.org/10.1016/j.jup.2025.102010
Received 31 May 2024; Received in revised form 14 July 2025; Accepted 14 July 2025
Available online 21 July 2025

including Kisumu's utility, the Kisumu Water and Sewerage Company (KIWASCO), since 2007 (Schwartz and Sanga, 2010). Under DMM, the utility recruits operators, either group-operators or individuals, to manage parts of its network through an open process, often in consultation with community associations from beneficiary populations (Castro and Morel, 2008). The utility delivers piped water in bulk to metered micro-operators, also referred to as Master Operators (MOs) in the Kisumu model, charging the micro-operators for bulk water provision each month. MOs thus serve as more than water retailers, because they operate and expand the local piped network. The MOs sell water to consumers, either piped connections to dwellings (hereafter termed domestic connections) or a network of water kiosks and standpipes for those unable to afford private connections, with the micro-operator generating its profits via higher tariffs charged from such connections. Kiosks are micro-enterprises that purchase water at a discounted tariff and then sell water to households lacking reliable domestic connections. A regulator, currently the Water Services Regulatory Board, oversees the tariff structures of micro-operators. Besides taking responsibility for revenue collection from households and water kiosks connected to the water network, the MO is further mandated to undertake minor maintenance of local infrastructure, thereby bringing service provision closer to the communities served. The micro-operator is also empowered to expand the network locally, acquire new customers, and reduce non-revenue water.

Previous studies evaluating DMM have highlighted its advantages. These include a more structured, hierarchical network, contrary to the unplanned 'spaghetti' network structure (Schwartz and Sanga, 2010; World Bank, 2009) that previously could evolve on its own (Fig. 1); reduced non-revenue water (World Bank, 2009); localized network expansion; and community involvement. These studies also identified further benefits, such as improved service delivery and professionalization in water management (Coppel and Schwartz, 2011), slightly lowered water costs for consumers (Nzengya, 2015), improved revenue for the water utility (KIWASCO) and employment generated through MOs and associated water kiosks/standpipe owners (Schwartz and Sanga, 2010).

The DMM, however, has not been without challenges. Initial studies highlighted ongoing illegal connections (Castro and Morel, 2008), though this had become scarce as per more recent studies (Nzengya, 2015); vandalism and meter thefts (World Bank, 2009, Schwartz and Sanga, 2010), corruption and misappropriation of revenue by MOs (Schwartz and Sanga, 2010), consumer hesitancy or lack of awareness over transferring to DMM, alongside limited commitment and support arrangements within KIWASCO (Schwartz and Sanga, 2010) as obstacles to DMM's future sustainability. More recent studies have further highlighted poor reliability in LIAs, including those with DMM (Nzengya, 2017) and meter theft (Nzengya, 2015).

To date, whilst evaluations of delegated management arrangements in Kisumu have examined its impacts on service delivery, affordability, employment generation, and tariff recovery as enumerated above (Schwartz and Sanga, 2010; Nzengya, 2015, 2017; Kemendi and Tutusaus, 2018), they have not been explicitly designed to assess water safety.

Some mechanisms could plausibly enhance the safety of water supplied in DMM areas, particularly for consumers with on-premises connections, in addition to other aspects of service delivery. First, DMM aims to increase domestic connections, thereby reducing the need for storing water collected from off-premises. Since post-collection recontamination of household stored water has been found in many settings (Wright et al., 2004; Shields et al., 2015) including Kisumu (Okotto, 2010), this should improve water safety for DMM households with domestic connections. Second, DMM aims to reduce water supply interruptions through a more rationally structured pipeline network (Schwartz and Sanga, 2010) and a community-based, locally accountable and responsive MO service (Castro and Morel, 2008). Thus, DMM should lessen the need for households with domestic connections to store water or use alternative, less safe sources as adaptations to supply intermittency. Third, bacterial contamination is often greater in interrupted compared to continuous piped systems (Kumpel and Nelson, 2013; Bivins et al., 2021), so fewer interruptions in DMM areas could further enhance water safety for households with direct connections.

DMM could potentially also marginally improve water safety for the programme's kiosk users. DMM aims to bring pipes and kiosks closer to consumers, thereby reducing water-handling and the potential for recontamination by handcart operators, who would otherwise transport water to households located farther from kiosks (Okotto et al., 2015). This model also reduces the risk of handcart operators selling cheaper, contamination-prone shallow well water to households as though it

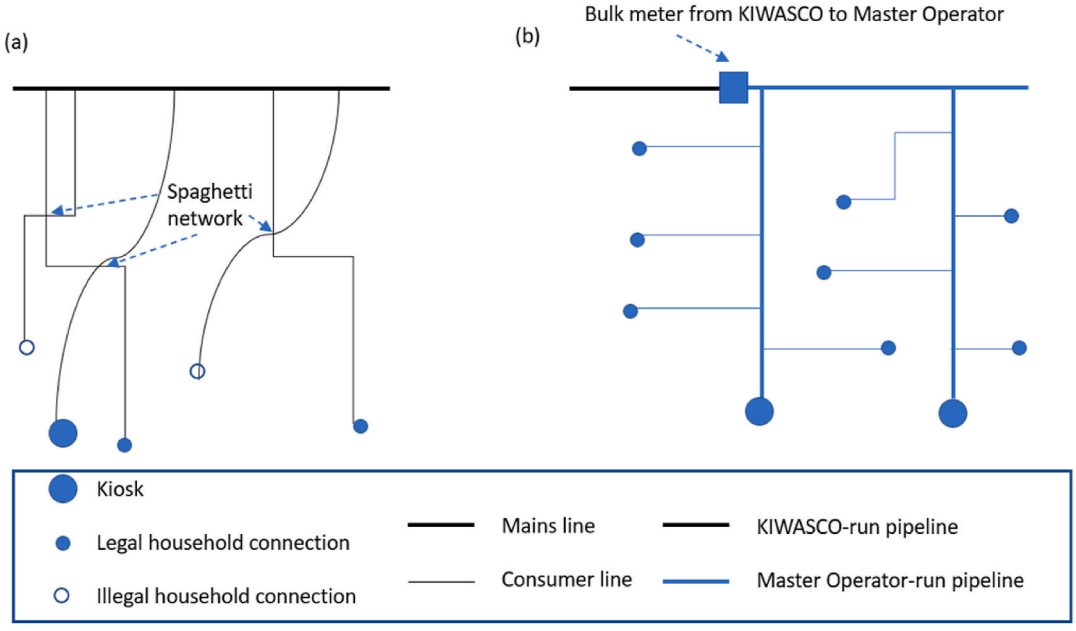

Fig. 1. Schematic diagram, illustrating the management and configuration of a piped water network (a) without delegated management and (b) with delegated management (adapted from (Nzengya, 2017)).

were kiosk water. In other respects, kiosk users in DMM and similar LIAs are likely to be exposed to similar recontamination and related risks. For example, given these areas' similar positions within the supply network, the risks of stored water recontamination due to inadequate free residual chlorine levels are also likely to be similar.

Our study aims to compare water safety (measured by thermotolerant coliform counts in MO pipelines, kiosks, and household stored drinking water) in DMM areas of Kisumu with comparable control areas through a post-hoc impact evaluation.

2. Materials and methods

2.1. Study area overview: Kisumu's delegated management model

As Kenya's third-largest city, Kisumu County's urban population was 441,000 in 2019 (KENYA NATIONAL BUREAU OF STATISTICS, 2019a). Unplanned urbanization has led to the growth of informal settlements around the city's planned core. In 2019, 49,200 (31.5 %) households in the three sub-counties containing the city had water piped to their premises, whilst 32.3 % used standpipes and 12.3 % used vended water (KENYA NATIONAL BUREAU OF STATISTICS, 2019b). The remainder, primarily the rural periphery, utilized a combination of rainwater, groundwater, and surface water. KIWASCO reported rapid growth in active piped water connections to households and kiosks from 23,862 in 2016 (KISUMU WATER AND SEWERAGE COMPANY, 2018) to 44,218 in 2021 (KISUMU WATER AND SANITATION COMPANY, 2022).

DMM operates under the supervision of a KIWASCO unit dedicated to underserved areas. As of October 2021, there were 49 MO pipelines and 41 active MOs with 8333 consumer connections in MO lines. MO pipelines served 7998 active kiosks or domestic accounts. Contracts with KIWASCO require that MOs "maintain water quality within the KIWASCO sub-network by ensuring that there is no contamination within the sub-network." Contracts also require MOs to "prevent pipe bursts and undertake immediate repairs within 24 h" and specify connection and meter fees for both households and kiosks, together with tariffs. However, they do not impose tariff structures on kiosks to pass on to their household customers. A social connection policy supports a customer's network connection cost, contractually set to a maximum of KSh2,700 (US$2.09) for MOs. MOs are billed for non-revenue water on the network that they manage, incentivising MOs to maintain the pipeline connecting them to the main network. KIWASCO imposes heavy sanctions for any unauthorized connections that are identified. Non-revenue water loss is charged at 10 times the standard rate and a fixed penalty fine of KSh 5000 (approximately US$32.95). KIWASCO patrols non-DMM areas to identify illegal connections but relies on MOs to identify and report such connections in DMM areas.

2.2. Sampling of Enumeration Areas

To identify control areas for comparison with DMM areas, map layers of sewerage pipelines, household water meters, water pipelines, kiosks, and DMM areas were obtained from KIWASCO. When site selection was conducted, small area boundaries, housing, and population statistics from the 2019 Kenyan Population and Housing Census were unavailable. Similarly, gridded population layers for Kenya (WorldPop, 2013, FACEBOOK DATA FOR GOOD, 2021) were modeled from population counts for sub-locations in 1999 or 2009. In the absence of more recent data, Enumeration Area boundaries (EAs; average population: 400) and associated population headcounts were obtained for Kisumu County from the 2009 census. To characterize building density, a map layer (GHS-BUILT-S2 R2020A) depicting the probability of built-up land cover per 10 × 10 m grid cell for 2018 (Corbane et al., 2020) was downloaded from the Global Human Settlement project. This map layer was derived from composite Sentinel-2 satellite imagery for 2018, classified using a convolutional neural network algorithm (Corbane et al., 2021). Pipelines under DMM were overlaid on EA boundaries to identify DMM areas. Rural EAs and EAs lacking a water pipeline were excluded, since the latter had no water supply infrastructure that could be delegated to micro-operators. Given that water may be transported short distances by Kisumu's households or vendors, we also excluded non-DMM EAs within 300 m of DMM pipelines to minimise potential spatial spillover effects (Benjamin-Chung et al., 2018).

We then quantified areal characteristics plausibly linked to microbiological contamination of source or household stored water as follows.

- Successive systematic reviews (Wright et al., 2004; Shields et al., 2015) have found widespread recontamination of water stored in the home (particularly of piped water), and such storage is essential where households lack on-premise water supply. We therefore created two metrics to compare on-premises versus off-premises water supply: the number of domestic water meters per household and the number of water kiosks per capita, respectively.
- Since crowded slum conditions are a plausible risk factor for water contamination, we calculated population density per EA in 2009. We also calculated the mean probability of built-up land cover per EA in 2018, derived by overlaying the GHS-BUILT-S2 layer on EA boundaries.
- Finally, since adequate sanitation reduces the risk of microbiological water contamination (Kirby et al., 2016), we identified EAs within 100 m of the sewerage network as a sanitation coverage metric.

Given that contamination risk factors are likely to differ between EAs under DMM versus other urban EAs with piped or kiosk water, we used coarsened exact matching (CEM) to select matched control EAs with similar contamination risk factor profiles to EAs under DMM. CEM is a form of matching, a set of methods that can be used to control for potentially confounding influences arising from pre-intervention differences between intervention and control area characteristics when making post hoc causal inferences (Iacus et al., 2012). Using the *cem* package within Stata version 16 software (Blackwell et al., 2009), we first assessed the imbalance in areal characteristics between EAs under DMM and other urban EAs with piped or kiosk water. We used CEM to reduce imbalance (i.e., differences in contamination risk factors) by matching the two groups of EAs, then randomly selected ten DMM and ten non-DMM matched EAs. During randomisation, a block of 30 EAs already randomly selected for a separate study of environmental waste (Umar et al., 2023) were prioritised for selection.

2.3. Sampling of MOs, kiosks, and households within EAs

Within each selected DMM EA, we listed and then selected MOs and kiosks on the MOs' network serving that area or, in control areas, those kiosks serving the EA's population. We also randomly selected handcart vendors selling water in jerry cans from these kiosks, as well as adult consumers buying water from handcart vendors or directly from the kiosks. We powered our sample to detect (alpha = 0.05; power = 0.8) a hypothesized 1 log reduction in baseline point-of-use thermotolerant coliforms (cfu/100 mL) from an initial median contamination level of 1024 cfu/100 mL in Kisumu's slums, with a 1 log standard deviation reported previously (Okotto, 2010).

2.4. Questionnaire surveys and water sampling

After seeking their informed consent, we administered questionnaires in English, Dholuo, or Kiswahili to MOs, kiosk and water handcart operators, and their adult customers, using tablets to record responses via the SurveyCTO software (Dobility Inc, 2021). Vendors and kiosk owner questionnaires covered business operations, prices, service interruptions, water storage, treatment, and handling, whilst household questionnaires covered housing conditions, water services, sanitation, and hygiene. Field teams directly observed water storage practices and the presence of water and soap at handwashing facilities. Fieldwork took

place between February 21 and June 15, 2022.

We obtained respondents' permission to collect a water sample for testing. We sampled piped water from the MO line, tap/kiosk, and handcart vended as well as household stored water collected from kiosks or vendors. Three samples of piped water were taken on consecutive days for each selected MO's pipelines to increase the probability that the sampling coincided with transient contamination events. Autoclaved 300–500 mL plastic bottles were washed with a non-ionic detergent and rinsed at least three times with distilled, deionized water prior to use for sample collection. Following sampling recommendations (Howard, 2002), taps were left to run for 2 min before collecting samples. Samples were tested in situ for free residual chlorine using SenSafe Water Check test strips, which are approved by the US Environmental Protection Agency (ITS Method 99-003). Water samples were transported on ice and analyzed in a laboratory at VIRED International, Kisumu, within 6 h of sampling.

Ethical approval was obtained from the ethical review committees of Jaramogi Oginga Odinga University of Science and Technology (REF: ERC/23/6/20-4; approval date August 19, 2020) and the Faculty of Environmental and Life Sciences, University of Southampton (ref: 55755, approval date: August 26, 2020). Human subjects research was carried out in accordance with the Declaration of Helsinki.

2.5. Laboratory analysis

Water samples were tested for faecal indicator bacteria, namely total and thermotolerant coliforms, using membrane filtration. A sample of 100 mL of water was filtered through a 0.45 μm pore diameter gridded cellulose acetate membrane using a vacuum pump. One millilitre of sterile quarter-strength Ringer's solution diluent was added to maintain cell isotonicity. The filtration unit was sterilised between each sample processing. Processed filters were placed on a Gelman absorbent pad pre-soaked in selective medium (Membrane Lauryl Sulphate Broth (MLSB) (Oxoid, Basingstoke, UK) in an aluminium Petri dish. The plate was then incubated at between 37 °C and 44 °C for 18–24 h in a Delagua DWT: 10098 kit portable incubator. After 24 h, golden yellow colony-forming units (CFUs) were enumerated as thermotolerant coliforms.

2.6. Statistical analysis

To quantify any residual differences in contamination risk factors after matching, we tested for differences in household characteristics between DMM and control areas. To evaluate plausible mechanisms that might reduce microbial contamination in DMM areas, we used the chi-square or Fisher's exact test to assess significant differences between DMM and control areas in supply continuity reported by kiosk owners, as well as the presence of tanks or water treatment at kiosks. We used linear regression to test for differences in free residual chlorine levels in kiosk water samples between DMM and control areas, as well as reported water prices. We calculated the population-weighted mean distance to the nearest kiosk per EA using QGIS 3.34 (QGIS.org, 2025), based on 100m × 100m gridded population estimates for 2020 (Bondarenko et al., 2020). We then used linear regression to test for differences between matched DMM and control EAs.

We graphically compared thermotolerant coliform counts from KIWASCO- and MO-managed pipelines, kiosk water, handcart vendor water, versus household stored water samples. Robust logistic regression was used to evaluate the association between DMM and detectable thermotolerant coliform levels (>0 cfu/100 mL) in household stored water, controlling for other known risk factors for water recontamination and clustering at the EA level. These risk factors included inadequate sanitation, hygiene, housing, and lack of solid waste management services in the home.

3. Results

3.1. Selection of intervention and control areas

Fig. 2 illustrates the number of EAs excluded from the study and subsequently matched, both within and outside the DMM framework. In all, 548 EAs were excluded because they were rural, lacked piped water infrastructure, or neighboured areas under DMM, and were thus unsuitable as controls due to potential spatial spillover effects. Of the 217 EAs (35.9 %) under DMM, 78 could not be matched to corresponding EAs directly supplied with water by the utility, KIWASCO, whereas 204 of the 348 EAs (58.6 %) not under delegated management were too dissimilar to be matched to areas under DMM. Ten DMM and ten non-DMM EAs were then selected at random from the remainder.

On average, prior to matching, EAs under DMM had greater population densities, were more built-up, further from sewerage pipelines, and had fewer domestic water meters and more water kiosks than other urban areas with piped water (Supplementary Table S1). The overall imbalance between DMM and non-DMM areas across all characteristics, as measured by an imbalance statistic (L1), was 0.74.

Following the exclusion of unmatched EAs via CEM, the overall imbalance was reduced (L1 = 0.48). Some differences between EAs under DMM and areas not under DMM remained (Supplementary Table S2), notably in population density, but the initial differences were substantially reduced following CEM.

Fig. 3 illustrates the locations of EAs excluded from the selection process due to being rural, lacking water pipelines, or being at risk of spatial spillover from DMM areas, alongside those that were matched or remained unmatched. The DMM areas typically lie in higher-density areas surrounding the city centre to the north, east, and south. They are more built-up compared to control areas. Non-DMM areas with piped water include the city's historic core and some other outlying neighbourhoods, such as those to the west and north of the city. Matched EAs are scattered throughout all zones but are more widespread in outlying non-DMM areas.

22 MOs were randomly sampled from the selected EAs with DMM. MOs were not present in non-DMM areas. During recruitment, it became apparent that hand cart operators were largely absent in DMM areas. We then sampled 91 kiosk owners (58 from DMM areas and 33 from non-DMM areas), and 11 water handcart operators (two from DMM areas with few handcart vendors, and nine from non-DMM areas). We further sampled adult household customers for the MOs and kiosks (131 DMM and 120 non-DMM households).

3.2. Differences in vendor and household characteristics between DMM and control areas

Kiosk operators reported lower supply continuity in DMM than in non-DMM areas (Table 1). These differences were significant when reported qualitatively (e.g., 'water available most of the time'), but not when reported as daily hours of water supply per week. Almost all kiosk operators reporting disruptions attributed these to either KIWASCO (79 % of 81 respondents) and/or MOs (62 % of 55 DMM respondents), as opposed to illegal connections or payment arrears. A minority of kiosk operators in both areas stored and treated water via chlorination, with treatment somewhat (but not significantly) more prevalent in DMM areas. Significantly more women were kiosk owners or managers in DMM areas. Kiosk operators in DMM areas were far less likely to sell water to handcart vendors than those elsewhere. Linear regression indicated that the mean population-weighted distance to the nearest kiosk was significantly shorter for DMM EAs compared to matched control EAs (605.7m versus 1027.5m, p = 0.001). Kiosk water samples had significantly higher free residual chlorine in DMM areas. There was no significant difference in water prices reported by kiosk operators between DMM and non-DMM areas. Among the 11 handcart vendors interviewed, two admitted to selling shallow well water in addition to

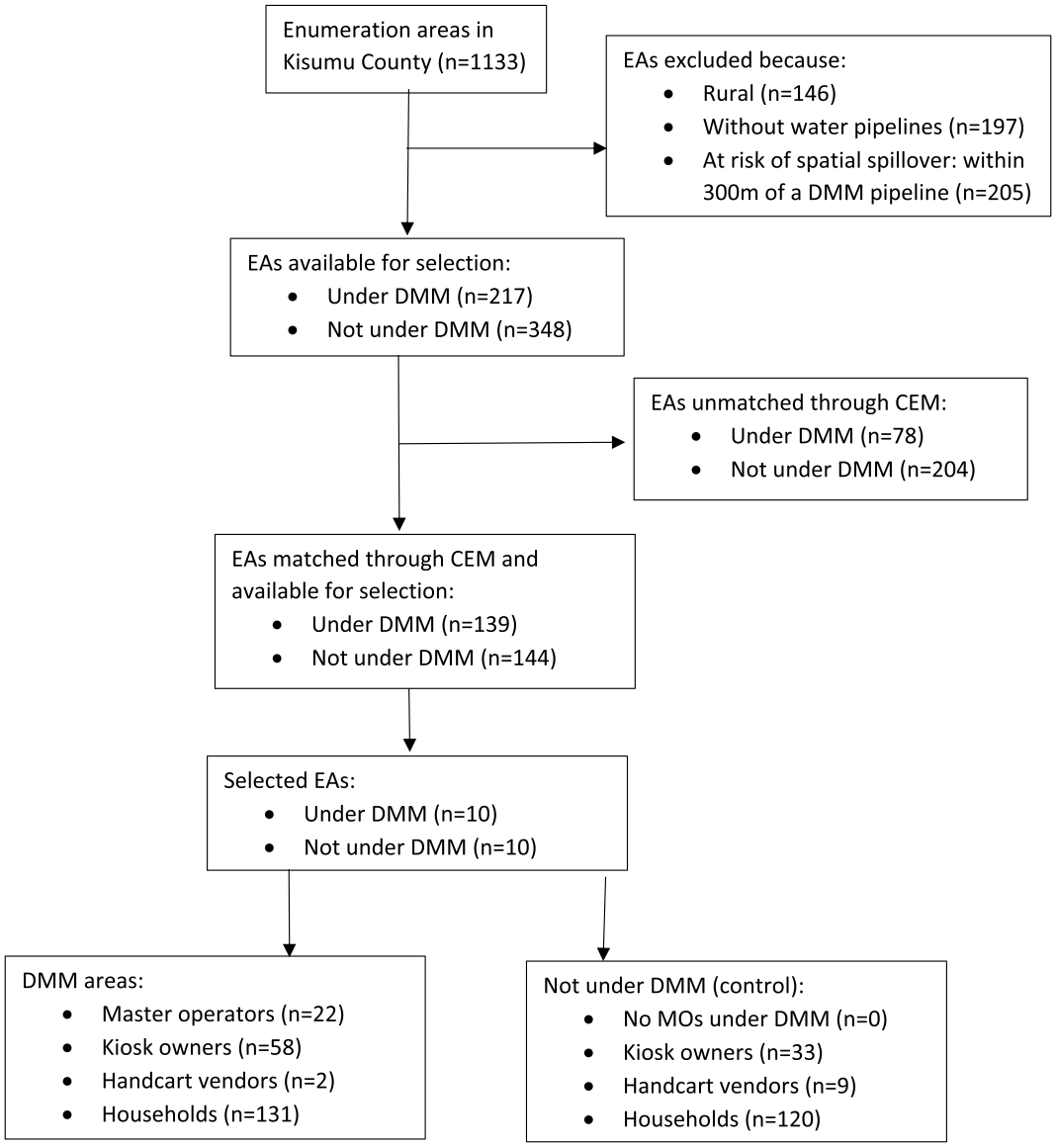

Fig. 2. Flow chart showing the selection of Enumeration Areas in Kisumu County, Kenya, and subsequent selection of master operators (MOs), kiosks, water vendors, and households.

piped water, and all were male.

When household characteristics were compared in DMM versus non-DMM areas (Supplementary Table S3), a significantly higher proportion of households lacked waste services and improved sanitation in DMM areas, suggesting poorer living conditions in these EAs, even after matching through CEM. No households reported insecure tenure of their homes. Despite DMM kiosk samples having higher residual free chlorine, free chlorine was significantly lower in household stored water in DMM compared to non-DMM samples (Table 2). Households generally reported higher water prices than kiosk operators, with significantly higher prices reported in DMM areas compared to non-DMM areas. Similar proportions of respondents were women, who were more often responsible for household water management than men ($p < 0.001$).

3.3. *Thermotolerant coliforms in DMM versus control water samples*

Samples were collected at four DMM kiosks following the interview, as water was unavailable on the day of the interview. Regardless of whether they were sampled from DMM or control areas, very few (4 of 161 samples) piped water, kiosk water, and handcart water samples had any detectable thermotolerant coliforms (Fig. 4). However, in both DMM and control areas, household stored water contamination was widespread, with 39.2 % (n = 130) of DMM samples and 36.4 % (n = 121) of non-DMM samples containing detectable thermotolerant coliforms.

When the association between DMM and detectable thermotolerant coliform levels in 100 mL of household stored water was examined through logistic regression, no significant differences were found between DMM and non-DMM areas (Table 3) for both the adjusted and unadjusted models (Table 3). None of the household risk factors included in either model was significantly associated with detectable thermotolerant coliforms, except for unimproved sanitation, which showed marginally significantly lower odds of contamination in the adjusted model.

4. Discussion

By increasing direct piped water connections, DMM should reduce the need to store water from off-premises, thereby lessening water recontamination. In both DMM and non-DMM areas, very few piped and

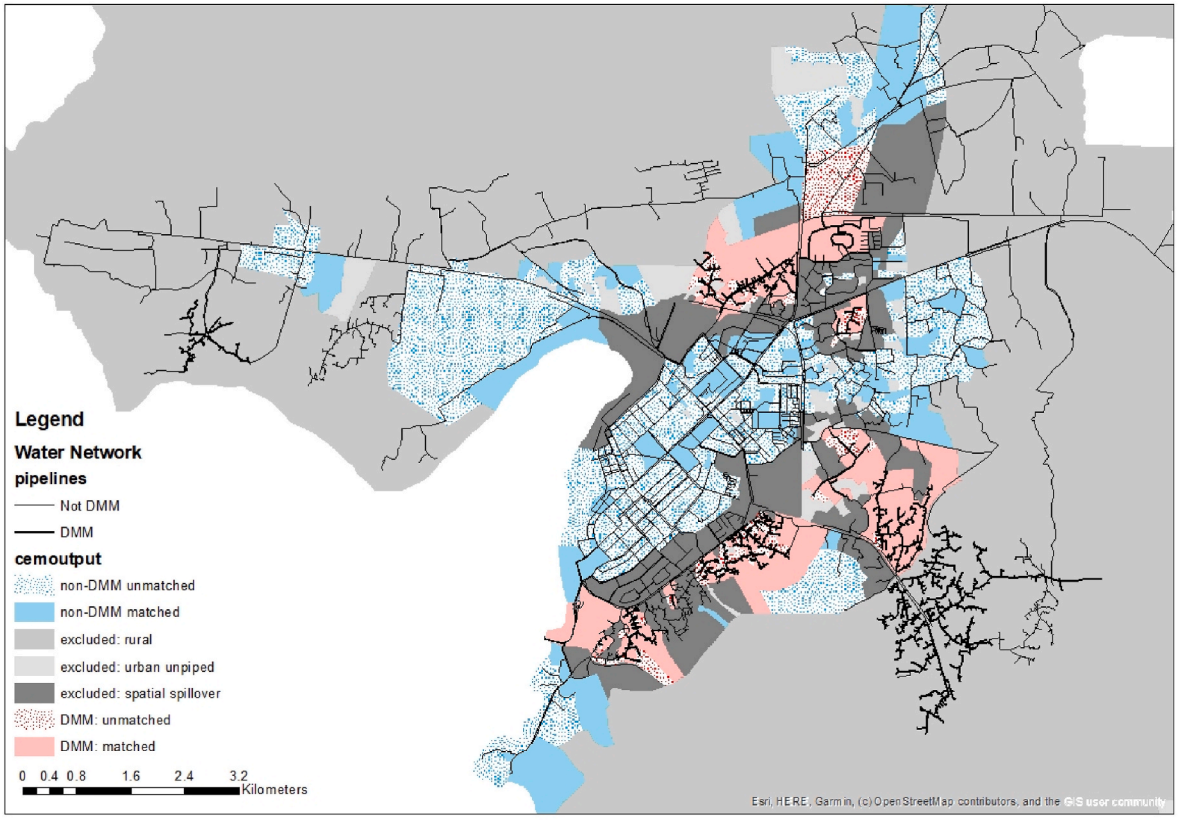

Fig. 3. Map of Kisumu, Kenya, depicting Enumeration Areas matched and unmatched via coarsened exact matching to those under a delegated management model of water services.

Table 1
kiosk characteristics in DMM versus control areas ([1]Fisher's exact test; [2]Chi square; [3]linear regression).

Characteristic	control areas (n, % of column)	DMM areas (n, % of column)	P value
Water continuity: Water always available	7 (21.2 %)	3 (5.6 %)	
Water is available most of the time	22 (66.7 %)	33 (56.9 %)	
Water is available some of the time	4 (12.1 %)	21 (36.2 %)	
Water rarely available	0 (0.0 %)	1 (1.7 %)	0.01[1]
Water supply in a typical week:			
24 h/day	1 (3.0 %)	4 (6.9 %)	
18–23 h/day	27 (81.8 %)	35 (60.3 %)	
12–17 h/day	5 (15.2 %)	10 (19.0 %)	
6–11 h/day	0 (0.0 %)	4 (6.9 %)	
<6 h/day	0 (0.0 %)	4 (6.9 %)	0.19[1]
Has a water storage tank	6 (18.2 %)	8 (13.8 %)	0.58[2]
Treats water (all via chlorination)	1 (3.0 %)	5 (8.7 %)	0.25[1]
Female kiosk owners or managers interviewed	11 (47.8 %)	40 (76.9 %)	0.01[2]
Sells water to handcart operators	13 (39.3 %)	3 (5.2 %)	<0.001[2]
Mean residual free chlorine in kiosk water (ppm, mg/L)	0.04	0.16	0.01[3]
Reported price of 20L of kiosk-vended water (KSh)	4.09 (US$0.027)	3.72 (US$0.025)	0.33[3]

Table 2
household characteristics in DMM versus control areas (P values derived from linear regression).

Characteristic	control areas (n, % of column)	DMM areas (n, % of column)	P value
Mean residual free chlorine in household stored water (ppm, mg/L)	0.09	0.03	<0.001
Reported price of 20L of kiosk-vended water (KSh)	4.32 (US $0.028)	5.18 (US $0.034)	0.003

kiosk water samples contained detectable thermotolerant coliforms. However, the water became contaminated during home storage (Fig. 4) due to post-collection recontamination, a phenomenon widely reported elsewhere (Wright et al., 2004; Shields et al., 2015) and in Kisumu (Barnes et al., 2018; Okotto, 2010). However, the number of kiosks and domestic connections via DMM has increased from 155 at the scheme's inception in 2008 (World Bank, 2009) to 7998 according to a 2021 KIWASCO report. Across Kisumu, the number of overall domestic and kiosk connections increased from 7852 in 2006 (World Bank, 2009) to 44,218 in 2021 (KISUMU WATER AND SANITATION COMPANY, 2022). Since the scheme's inception, such DMM connections have grown more rapidly than direct utility connections, with DMM accounting for 18.1 % of all connections in 2021 compared to an estimated 6.2 % in 2008. Thus, DMM has accelerated and sustained domestic connection coverage, reducing exposure to recontaminated water. It has thereby also reduced population exposure to faecal contamination from alternative unsafe sources, notably Kisumu's highly contaminated shallow wells (Okotto-Okotto et al., 2015). Furthermore, in our study, detectable thermotolerant coliforms in piped and kiosk water samples were significantly lower than the 26.1 % rate reported in 46 piped samples from Kisumu in 2009 (Okotto, 2010), indicating long-term improvement in the city's piped water safety.

In comparison to non-DMM kiosks, our study reveals comparable faecal contamination of DMM kiosk water at the point of consumption

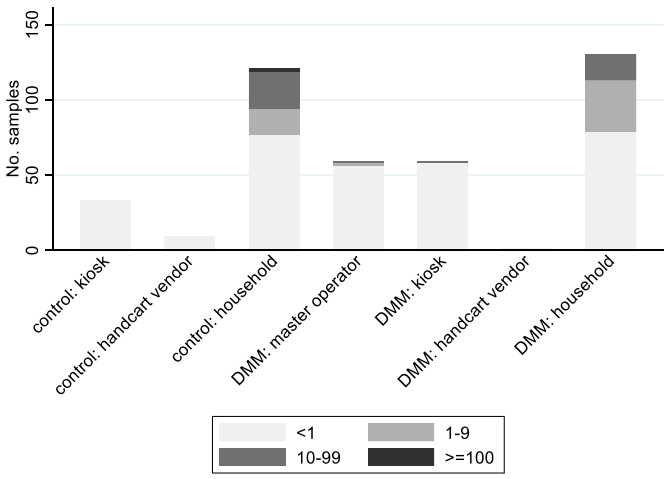

Fig. 4. Thermotolerant coliform counts (colony forming units, cfu/100 mL) in water samples taken from KIWASCO-managed pipelines, Master Operator-managed pipelines, water kiosks, water vendors, and household stored water in areas under delegated management (DMM) versus control areas not under DMM.

(Table 3), suggesting that DMM kiosk users continue to be exposed to water contamination. Our study provides mixed evidence on the underlying mechanisms of water contamination in DMM compared to control areas. It was initially envisioned that DMM would bring pipes and kiosks closer to consumers (Schwartz and Sanga, 2010), thereby cutting out some water-handling steps and reducing potential recontamination. While our microbiological testing showed no evidence of recontamination of handcart-vended water (Fig. 4), we found that handcart vendors were largely absent from DMM areas, as anticipated. DMM kiosks were significantly closer to consumers, enabling households to purchase water directly from the kiosks rather than through handcart operators. DMM has thus largely eliminated the potential risk of these vendors selling water from shallow wells, which are known to be heavily contaminated (Opisa et al., 2012; Okotto-Okotto et al., 2015), as opposed to piped water. In effect, DMM has increased supply chain formality, replacing informal handcart operators with formalized kiosks and micro-enterprises. In doing so, as previously highlighted in Kisumu (Nzengya, 2015) and as intended, DMM provides women with greater employment opportunities (Table 1). As anticipated, evidence regarding inadequate free residual chlorine in water was equivocal, with significantly higher residual chlorine levels in DMM kiosk samples (Table 1) but lower residual chlorine levels in DMM household stored water (Table 2) compared to control areas.

However, the potential benefit from reducing handcart operators is offset by lower piped water continuity in DMM areas (Table 1) relative to control areas. This finding is counter to those of earlier DMM evaluation studies, which either found more reliable water supply in DMM areas or continuous water supply across all LIAs. For example (Kemendi and Tutusaus, 2018), reported continuous water supply throughout Kisumu's LIAs. In a 2013 study in Kisumu (Nzengya, 2017), between 81 % and 93 % of kiosk operators and customers reported unreliable piped supply, with higher unreliability of supply reported in non-DMM areas. If households and kiosks connected to DMM areas experience more supply disruptions than non-DMM areas, then this incentivises households and kiosk operators to store water, exposing this population to post-collection faecal recontamination.

Furthermore, DMM households reported higher prices for kiosk water compared to control households, though prices reported by kiosk operators were similar. In 2013, the opposite – lower kiosk prices in DMM areas – was reported (Nzengya, 2017). Prices in all areas were over double the KSh2 (US$0.013) mandated by the regulator, the Water Services Regulatory Board (Water Services Regulatory Board, 2021). Such higher prices in DMM areas could also incentivise the use of unsafe alternative water sources and run counter to DMM's objective of delivering affordable water services. Reports from the KIWASCO unit dedicated to DMM indicated that most MOs owed the utility substantial sums of money, with one MO owing Ksh1,000,000 (approximately US $6590) and others owing up to KSh500,000. Greater interruptions and higher prices within DMM areas may, therefore, reflect financial pressures on DMM micro-enterprises and a need to recoup costs or delay maintenance operations and payments. Reported supply interruptions in both DMM and control area kiosks are likely related to financial and operational management issues, rather than water production, because KIWASCO has sufficient water capacity from both Lake Victoria and a new production plant to meet projected demand to 2030 (Kemendi and Tutusaus, 2018).

KIWASCO's 2021 annual report notes its aim for a "reduction of (the) number of kiosks by expanding direct connections" (KISUMU WATER AND SANITATION COMPANY, 2022) in LIAs. Greater coverage of in-house domestic connections would reduce the need for household water storage and thereby the risk of post-collection faecal contamination of household stored water. Thus, the KIWASCO strategy of treating kiosks as an interim form of household supply to be phased out in the longer term should also reduce population exposure to faecally contaminated drinking water. As an interim provider-led service (Ray and Smith, 2021), DMM's kiosks deliver other benefits to consumers in the meantime. They provide an alternative to contaminated shallow well water for households unable to afford domestic connection fees, sustained via the kiosk business model. In DMM areas, they are significantly closer to consumers, thus likely generating time savings for households when fetching water.

The use of spatial data for constructing comparator groups and robustly evaluating the impact of non-randomised, community-based interventions in WASH remains limited, despite the difficulties that imbalance (systematic differences in characteristics linked to intervention outcomes between areas with and without a programme) poses. Our study highlights the potential to utilize matching techniques, such as CEM, in combination with geospatial data to mitigate covariate imbalance when conducting impact evaluations. In contrast to previous evaluations of Kisumu's DMM programme, which either had no comparison group (World Bank, 2009; Schwartz and Sanga, 2010; Kemendi and Tutusaus, 2018) or purposively selected a comparison group (Nzengya, 2015, 2017), we sought to minimise imbalance by using CEM to select a control group. More generally, given the increased

Table 3
Unadjusted and adjusted odds ratios for risk factors for detectable thermotolerant coliform counts in 100 mL of household stored water.

Covariate	Detectable Thermotolerant Coliforms (>0 cfu/100 mL), no. samples (%)	Unadjusted Odds Ratio (95 % CI)	P Value	Adjusted Odds Ratio (95 % CI)	P Value
DMM area	52 (39.7 %)	1.18 (0.59–2.34)	0.639	1.19 (0.71–2.01)	0.51
Unimproved sanitation	27 (34.2 %)	0.79 (0.52–1.20)	0.276	0.67 (0.47–0.95)	0.03
No handwashing facility or a facility lacking soap and water	68 (38.0 %)	1.02 (0.48–2.19)	0.96	1.13 (0.52–2.43)	0.76
Overcrowded housing	27 (39.1 %)	1.07 (0.89–1.31)	0.44	1.05 (0.84–1.32)	0.65
Non-durable housing	19 (39.6 %)	1.09 (0.77–1.57)	0.62	1.11 (0.78–1.58)	0.55
Lack of solid waste services	87 (39.6 %)	1.66 (0.34–10.55)	0.47	1.90 (0.37–9.84)	0.76

availability of spatial databases and digital records within African utilities, such as KIWASCO and Nairobi's water utility (Mutono et al., 2022), there is a growing opportunity to utilize this data for programmatic evaluation.

Our study findings are subject to several limitations and uncertainties. By focusing narrowly on water safety, our study did not quantify DMM's wider potential benefits, notably reduced time spent fetching water by female household members. We tested for thermotolerant coliforms as a recognised faecal indicator bacteria group, but did not test for the broader range of pathogens potentially present in drinking water (Gleeson and Gray, 1997). We also sampled vended and household-stored water once and piped water on three occasions, thereby potentially missing transient water contamination events. CEM also has some known limitations despite its advantages. For example, since some non-matched units are dropped from analysis during CEM, if treatment effects are heterogeneous, this can bias treatment effect estimates (Black et al., 2020). CEM-derived estimates can also be sensitive to the choice of covariates used for balancing. Some protective or risk factors for post-collection water contamination were not measured and controlled for in our logistic regression analysis, notably the presence of animals in the home (Barnes et al., 2018) and household water treatment, storage, and handling practices. There may thus have been unmeasured systematic differences in these risk factors between the DMM and control areas, which could have affected our findings.

5. Conclusion

Our findings highlight several avenues for further research. First, given the transient contamination events that affect piped systems, there is potential in the future to utilize online continuous residual chlorine sensors (Wilson et al., 2019) to evaluate programs such as DMM, which aim to improve the quality of piped water in municipal utility networks. Second, despite it being a stated DMM goal (World Bank, 2009; Castro and Morel, 2008), quantitative evidence is lacking concerning DMM's impact in reducing 'spaghetti' pipelines and generating a more logical, coherent piped infrastructure configuration. Finally, the underlying causes of higher prices for kiosk water in DMM areas (Table 2) require further investigation, given that more affordable water services were an intended objective of DMM (Castro and Morel, 2008).

Overall, our study findings provide evidence to inform the planning of partnerships between utilities and micro-operators elsewhere. DMM has likely contributed to reducing population exposure to recontaminated stored water by accelerating and sustaining household domestic connections, thereby reducing the need to store water from off-premises sources. Furthermore, piped and kiosk water contamination in our study is lower than reported in previous studies of Kisumu. Regardless of whether kiosk water consumers reside in DMM or other LIAs, they are similarly exposed to high recontamination of household stored water. KIWASCO's long-term strategy to replace kiosks with direct household connections is expected to reduce this public health risk. Kiosks are closer to consumers in DMM areas, which consequently have fewer handcart vendors, lessening potential recontamination risks from water handling. However, DMM kiosk operators report poorer water continuity, and households report higher kiosk prices. Both may incentivise households to store water or use other unsafe sources such as shallow wells. DMM remains a viable, sustainable, and responsive service delivery model, but other strategies are needed to address post-collection contamination of household stored water.

CRediT authorship contribution statement

Lorna Grace Okotto: Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Joseph Okotto-Okotto:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Peggy Wanza:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Jim Wright:** Writing – original draft, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Funding

This research was undertaken through the 'Expanding safe water and waste management service access to off-grid populations in Africa' project funded through a UKRI Collective Fund award via the Global Challenges Research Fund (ref: ES/T008121/1). The support of the UK Economic and Social Research Council (ESRC) is gratefully acknowledged. The funder had no role in the study design, data collection, analysis, or interpretation.

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.

Acknowledgements

We gratefully acknowledge the assistance of Sally Okumu of the Kisumu Water and Sewerage Company in supporting community liaison and providing additional background and documentation on the DMM scheme.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jup.2025.102010.

Data availability

Gridded map layers depicting the probability of built-up land use are available from the Global Human Settlement programme at https://ghsl.jrc.ec.europa.eu/download.php. Kenyan population census data are available upon request from the Kenya National Bureau of Statistics (https://www.knbs.or.ke/data-request/). Water infrastructure map layers for Kisumu are available, subject to approval from the Kisumu Water and Sewerage Company (https://kiwasco.co.ke/contact-us/). Gridded population counts for Kenya in 2020 are available from: https://hub.worldpop.org/geodata/summary?id=49694.

Household and water service provider questionnaire survey data, together with associated water quality test results, are openly available from:

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Glossary

CEM –: coarsened exact matching
cfu –: colony-forming units
DMM -: Delegated Management Model
EA –: Enumeration Area
KIWASCO –: Kisumu Water and Sewerage Company
LIA –: Low Income Areas
MO –: Master Operator
SDG –: Sustainable Development Goal
SSA –: Sub-Saharan Africa