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The structure of informal water markets: Insights from spatial monitoring in Lodwar, Kenya

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Abstract

Public water utilities have struggled to keep pace with rapid urbanization, particularly in towns and small to medium-sized cities of low-income regions. Informal water markets have proliferated to fill gaps in piped water coverage and service delivery through a wide range of water vending activities (from private water sources to tanker trucks and handcart operators that distribute water). Despite the prevalence and persistence of water vending, the structure, impacts, and evolution of informal water markets in these settings remain poorly understood, especially the interaction between private vendors and public utilities. We seek to improve our understanding of mobile, distributing vendors (tankers, motorcycles) by advancing high-frequency, spatially explicit monitoring of water vendor transactions in Lodwar, Kenya. We examine both the market and spatial structure of the informal water supply system and then draw inferences about their impacts and evolution. We find that vendors that use motorcycles are not making profits from transporting water. We also identify many linkages between the formal and informal systems. For example, purchases of bulk water by water vendors account for 28% of the public water utility's revenue. We also find that while most consumers of vended water are located outside of the piped water service area, many households and institutions inside the service area still purchase from private water vendors due to concerns about reliability and quality. These results highlight the complementarities between public utilities and private water vending and the corresponding importance of mapping water vending networks to support planning, policy, and investment and to protect consumers.

this research. Interested researchers may direct data access inquiries to the Oxford University ethics office at curec@ouce.ox.ac.uk.

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Introduction

City planners and water managers have struggled to ensure water service delivery keeps pace with rapid urbanization and the effects of climate variability in many parts of the world. Gaps in piped water services at the peri-urban fringe combine with stubborn pockets of exclusion within informal settlements, leading to plumbing poverty – a term used to describe inequalities of piped water access in the home [1]. In this context, informal water provision has proliferated in the form of small, independent water providers operating in the absence of regulation or in defiance of it [2], giving rise to decentralized water services that operate in the informal sector [3,4]. These small water enterprises operate across the supply chain from private water sources to mobile distributors and a range of value-added services (e.g., treatment, packaging) [5,6]. The resulting archipelago of water provision [7] has contributed to an uneasy détente between public water utilities and the informal sector, which is frequently ignored during water service delivery planning or stigmatized as "merchants of thirst" [8] operating in illegal and predatory ways, e.g., as documented in Jordan and Lebanon [9,10].

Research on water vending is growing as informal water vending has proliferated and persisted [11–13]. Informal water vendors span a diverse range of different types of small-scale, private water service providers, operating in the absence of regulation. In one of the early studies of water vending, Whittington and colleagues [6] classify vendors into three types: wholesale vendors (water sources), distributing vendors (mobile delivery), and direct vendors (fixed points, where consumers travel to purchase water). These three types of vendors are linked through supply chains that often include a mixture of public and private elements, such as public wholesale vendors accessed by private distributing vendors, and a mix of both public and private direct vendors [5,14]. Engagement by utilities with informal water providers has also grown, creating what some have described as mixed systems, hybrids, and a "meshwork" that makes accountability for service provision more challenging [15]. For example, Sarkar [14] notes that in Nairobi "local authorities now realize that the main reason for the growth in the alternative service market is their own failure to deliver an adequate public service" which has led in some instances to utilities working with "authorized private water providers to make supply arrangements for low-income areas" (pg. 455).

Numerous researchers have focused on whether, and under what conditions, water providers in the informal sector can contribute to the human right to water, the sustainable development goals on water, and a wider set of discipline-specific concerns [2,5,6,11,16]. In the absence of data and information about the benefits and risks of water vendors, myths persist, raising pressing questions for academics and practitioners about the structure of informal water markets, their evolution, and impacts. Answering these questions in turn requires tackling measurement challenges to generate high resolution data. We can then develop our understanding of the dynamics of water vending in relation to shifting social and environmental conditions, such as patterns of urbanisation, infrastructure coverage, and public health risks from weather shocks or pollution.

We examine the provision of water by informal vendors in Lodwar, a municipality in Northwestern Kenya. Sub-Saharan Africa is experiencing rapid urbanization, particularly in towns with less than one million people [17]. These small- and medium-sized towns frequently lack financial and governance capacity when compared with larger towns [17,18]. As a result, residents of smaller cities have lower levels of access to basic public services, including piped water and wastewater collection and treatment compared to residents of larger urban centers [19–22]. These trends have contributed to inequalities in water access, particularly at the expanding boundary of the town, an experience occurring across rural-urban infrastructure networks around the world [23].

Informal water markets are a common response to these gaps in infrastructure coverage and reliability. In East Africa, private, small-scale water vendors were among the diverse forms of water supply recognized over 50 years ago in *Drawers of Water* [24]. Recently, informal water vendors and small water enterprises have been found to supply anywhere from 7% to 100% of the population sampled (100% has been found in post-conflict zones and humanitarian crises where vendors are the only option) [2]. Informal water vending has been recognized as a response to a few types of water infrastructure supply challenges. It is found in places not served by piped water [10], where piped water supply faces frequent service interruptions, due to climate variability or supply inadequacy [9,25,26], and where piped water quality is perceived to be poor [27].

Water vendors have been researched extensively in East Africa, particularly in the 25 years since the Millennium Development Goals were adopted, aligning with a period of decentralization and growing integration of kiosks into water supply systems. Empirical research in the region has clustered in Tanzania [28,29] and Kenya [22,26,30,31] with more limited coverage in Ethiopia [30] and Sudan [32]. These studies draw on a range of disciplinary perspectives including economics, geography, and development studies which has led to limited consistency in measurement and monitoring [33]. Kenya is among the most extensively studied in the region. Informal water vendors have been found in informal settlements with high levels of poverty and inadequate provision of water services in Nairobi [14,34], cities with historically poor piped water coverage such as Kisumu [26,35], and the small coastal village of Ukunda, where one of the earliest studies of vending occurred [6]. Climate variability, punctuated by extreme droughts and floods, has led to emergency investments by government in mobile vendors. There has been a growing trend toward recognition and integration of such vendors into water service delivery planning and co-production arrangements [15,25,36]. For example, the Kenyan Water Services Regulation Board (WASREB) issued its Guideline on Water Vending in 2019 followed by a public notice in early 2023 requiring tankers to register.

Informal water markets remain poorly understood in terms of their structure, impacts, and evolution, especially in relation to the formal water infrastructure system [9,10]. Research on informal water markets has been limited due to the challenging nature of studying informal businesses – business information may be regarded as trade secrets and accurate data are difficult to collect [5]. There is inconsistency in the types of data collected and the sampling frames used [33]. There is also limited insight into the structure of the market and its spatial and temporal patterns [2]. Furthermore, there has not been any high-resolution, longitudinal monitoring to be able to address questions around dynamics, pathways, and long-term impacts.

Our study makes two key contributions in advancing understanding of the structure of informal water markets. First, we describe the spatial and market structures in Lodwar in relation to the existing public infrastructure. We characterize the spatial patterns of the water market. Identifying spatial patterns yields insights about a city's growth patterns and its changing needs for water infrastructure. In understanding market structures, we build upon previous work done in Ukunda, Kenya [6] and Kathmandu, Nepal [5]. We characterize the market structure of water supply in Lodwar by (1) describing the flows of money and water from and to the water utility and informal water markets, (2) building a typology of water vendors, and (3) assessing profitability of informal water vending businesses. This allows us to better understand the economics of informal water businesses, as well as the institutional arrangements of water supply between actors: vendors, water utilities, government, NGOs, and other private firms. Second, we advance a high-frequency and spatially explicit methodology that can be used to understand the spatial patterns of informal water markets, building on past work integrating GPS tracking with survey data collected through in-person interviews [37,38]. Our study demonstrates proof-of-concept of high frequency, spatial data collection of water vending systems and frames future research questions.

In the next section, we describe the methods used, including the case selection, background, fieldwork and data collection, and analysis. In the results section, we provide an overview of informal water vending in Lodwar and detail our main findings – the role of water vending in relation to the piped water infrastructure, its spatial structure, and market structure. We then examine the significance of our results in the discussion section and draw broader inferences with reference to future work in the conclusion.

Methods

Ethics statement

The study followed ethics protocols at the University of Oxford (approval # SOGE 18A-48) under the permit granted by the Kenyan government for the REACH programme (https://reachwater.uk/) led by the University of Oxford. A multi-layered approach to research ethics ensured this project has been positioned within a broader, long-term (10 years) research partnership, including collaborations with local research teams and water managers (including co-author Mr. Ekwar). Permits were provided by the University of Oxford Central University Research Ethics Committee (CUREC) and Kenya National Commission for Science, Technology and Innovation (NACOSTI).

Recruitment of participants occurred from May 21st to August 4th, 2018, following a workshop in early May 2018 to introduce the study and seek feedback from partners and stakeholders at UNICEF, the local utility, vendors, and government officials; additional consultations with key informants has occurred periodically since the primary field data collection, including a report back to stakeholders of the preliminary findings in December 2018 and a public workshop in February 2019 to present and discuss the research with study partners and participants. Participation was strictly voluntary and guided by free and informed consent with particular attention to working with vulnerable populations operating in the informal sector [39]. Verbal consent was chosen because it is the best option to protect the interests of participants. The collection of participants' signatures could potentially create harm [40,41]. Verbal consent is preferable in situations with (1) low literacy, (2) cultural or political concerns signing contract-like documents, (3) risks for the researcher or subject if the paper record is discovered by authorities, and/or (4) limited time to gain consent [42]. For example, prior studies on water vending in East Africa have noted that "fear by some people that participation could lead to problems—given the illegal nature of some of the water reselling activities" [30]. Written consent in such situations may raise risks by creating a contract-like and paper record that could either put participants at risk if discovered by authorities or create fears that discourage their participation.

We took steps to ensure that verbal consent was understood and agreed in two ways. First, we used "talk-back" methods that included pauses and allowed subjects to tell the researcher what they have heard and demonstrate whether they understood it in their own terms. Second, enumerators were trained in the consent process and required also to document consent via checkbox in the tablet version of the interview and survey instruments. At the beginning of the interview with all participants, the participants had the opportunity to ask questions before giving verbal consent to each component of the interview as outlined in the consent form. The verbal consent process also allowed us to get participants' consent for distinct elements whilst allowing for the participant to ask questions directly. In the informed consent process, participants were made aware that they can stop participation at any time, either for questions and clarifications, or to withdraw. In line with the PLOS Inclusivity in Global Research principles, additional information regarding the ethical, cultural, and scientific considerations specific to inclusivity in global research is included in the S2 Text.

Case selection and background

Our research addresses measurement challenges in studying informal water vending, with a primary focus on monitoring distributing vendors. Distributing vendors lack visibility due to their mobility when compared to other, stationary parts of informal water systems. Existing approaches rarely include spatially explicit data and the repeat observations needed to understand the structure, evolution and activities of vendors (but see [37,38]). Our goals with this study were exploratory and focused on proof of concept. The case selection strategy for descriptive-exploratory case studies is to choose cases where the phenomenon of interest is present and readily observable, which poses unique challenges in the context of informality and quasi-legal transactions. We selected a case that possesses three key characteristics: (1) a rapidly urbanizing town in a low-income country, (2) inadequate and intermittent piped water supply, prompting alternate types of water supply, and (3) active informal water markets (the phenomenon of interest).

Lodwar offers a good fit for this study because it is experiencing rapid changes and is supported by pre-existing research partnerships. First, Lodwar has experienced a rapid transition from a rural town to a small urban centre, becoming a municipality on December 5th 2018 under the Urban Areas and Cities Act, in recognition of population growth and preparation of an integrated development plan. The resulting charter called for the municipality to promote and provide water and sanitation services in areas unserved by the utility (see below), but capacity to fulfil these roles has proven limited. Like many towns and small cities experiencing rapid changes in low-income settings, Lodwar's growth has outstripped already strained water supplies and services. The population grew from 58,290 to 2009 to 82,970 by 2019, an increase of over 40% that only partially accounts for pastoral and internally displaced populations [43,44]. Lodwar is located in the northwest corner of Kenya in Turkana, the poorest county in the country. The area is subject to land disputes. With respect to connectivity, Lodwar is remote and difficult to reach despite growing flight access and the development of new road infrastructure from Kitale to Lodwar. Many households rely on food aid, payments in kind, crops and wild food, transfers, and casual employment [45,46]. As an urbanizing area distant from Nairobi, the region exemplifies the blindspots [17] in our understanding of "fast-growing small- and medium-sized cities" which "generally lack financial and governance capacity" and hence rely disproportionately on informality and locally tailored solutions to problems of water scarcity (35,36,37)

Second, Lodwar's water system and services have failed to keep pace with growth, prompting coping strategies and alternatives to piped water networks. Lodwar is arid, with a hot, dry climate. Annual rainfall is low and variability is high. Droughts and flash floods are common [47,48]. The city depends on the Turkwel river to recharge the Lodwar Alluvial Aquifer System (LAAS) which is the main long-term water resource [49]. Upstream abstraction by irrigated agriculture and uncertain release patterns from the Turkwel Gorge dam pose risks to the city's water supply. The LAAS has an estimated one billion m^3 of water, of which only a small percentage may be sustainably abstracted [49]. Groundwater is the current and only long-term public source for drinking water services in Lodwar. Households in Lodwar without connections also rely on water from the two local rivers: the Turkwel, a perennial river, and the Kawalase, a seasonal river. Water quality concerns affect both sources. In Turkana, high levels of fluoride limit the development of the groundwater aquifers [50,51]. The municipal boreholes are affected by climate risks including dry seasons, sustained droughts, and destruction by flash floods [48,52].

Finally, inadequate water services have led to a significant supply gap filled in part by water vendors. Informal water vending is prevalent due to unreliable water services and associated challenges of utility tariff structure and cost recovery, which limits investments in extending and improving piped water networks (37,44). Water services in Kenya have been devolved under water legislation in 2016. The public water utility in Lodwar (until late 2023, Lodwar Water and Sanitation Company or LOWASCO) has ranked in the bottom half of utilities due to management, operational, and financial challenges. Approximately 54,000 of Lodwar's nearly 95,000 residents have piped connections served by the utility according to the national IMPACT report released in 2023 [53]. LOWASCO's non-revenue water is estimated to be 40%. In November 2023, LOWASCO was disbanded and replaced by the Turkana Urban Water and Sanitation Company, also based in Lodwar and operating across Turkana County [54].

Fieldwork and data collection

We conducted the primary fieldwork in Lodwar from June to July, 2018. The data collection happened in three stages (see S1 Text). First, we conducted a census of water vendors in order to build a systematic sampling frame. This included both mobile water vendors (that use tanker trucks, tractors, and motorcycles to transport water) and vendors selling from point sources (private taps, boreholes, and kiosks). A brief baseline survey was conducted during the census. At the time of the study and its primary field season (2018), registration of mobile vendors (tanker trucks, tractors, and motorcycles) was not required and thus these vendors largely operated in the absence of regulation. Second, we tracked the trips made by mobile water vendors using repeat questionnaires and GPS devices (operated by enumerators) over a period of seven weeks. Finally, we conducted 17 key informant interviews and eight focus group discussions during this fieldwork period in order to form a holistic understanding of the water supply system in Lodwar and track key dynamics. On the basis of these long-term partnerships, we have consulted with key informants periodically, including follow-up interviews in October and November 2024 to determine whether the 2019 Guideline on Water Vending has been implemented in Lodwar. We confirmed that the Guideline (and associated registration requirement) has not yet been fully implemented in Lodwar (see also the discussion below).

To conduct the census, we used several techniques: (1) walking and driving for three days around town and its surrounding areas, and visiting known "stages", where vendors wait for customers, (2) obtaining a list of registered vendors from the water utility, (3) using a snowball sampling technique that quickly reached the point where we did not identify any new vendors, and (4) compiling a list of water sources used by the mobile vendors (by talking with point source vendors—both publicly and privately owned). We identified 22 tanker vending business owners (with 35 tanker trucks and tractors), 107 motorcycle (*boda bodas*) that transport water at least once per week. We identified 19 private source vendors (private boreholes), in addition to five LOWASCO kiosk managers.

The census was followed by a short, introductory baseline questionnaire, where we obtained information about the operations of mobile vendors (focusing on the water sources, volumes transported, both sale price and cost of water), customers, and challenges faced. The baseline questionnaire also served to begin building trust with the respondent in order to encourage participation in the second, or tracking, stage.

In the second stage, we tracked the trips made by mobile water vendors using GPS devices and a trip log, or diary, over a period of seven weeks. Tankers were opportunistically sampled and motorcycle vendors were stratified by volume and then randomly selected. Tracking the trips made by water vendors was done both with and without an enumerator in order to validate the remote tracking method. Once a week for seven weeks the locally recruited enumerators accompanied the water vendors on their daily trips (with the day of the week randomly selected). The enumerator recorded (1) the paths taken using their GPS tracker (a Samsung tablet running Android v4.4.2 using Ultra GPS Logger, an off-the-shelf smartphone application), (2) information about prices, costs, and quantities of water transported, and (3) consumer characteristics and feedback when available. The vendors were also asked to (1) record their trips during the week using a trip log and (2) to track their own trips using GPS devices (GlobalSat DG500). Vendors were compensated for their time and participation in the study – 500 KSH/week (US$5/week based on the exchange rate: approximately 100 KSH to 1 USD during the study period of June 2018) and 1,000 KSH/week (US$10/week) for those with their own GPS devices (capable smartphones).

In the third stage, we interviewed key institutional actors and communities unserved by the piped water network. For the key informant interviews, we met with politicians, government officials in the Ministries of Water, Public Health, and Planning, utility managers, NGO employees and leaders, bureaucrats in regulatory agencies related to water resources and the environment. We wanted to understand (1) their roles in water supply and future plans and (2) their interactions with and perceptions of water vending – water vendors' past, present, and future role in water supply. We created a semi-structured interview guide and followed standard social science qualitative interview techniques [55–57], focusing on elite interviews [58,59]. For the focus group discussions, we focused on three neighborhoods in Lodwar– Kawalase, Nakwamekwi, and Juluk (in Kanamkemer). The objective was to better understand the customers in areas that are served by water vendors that transport water (Kawalase) and similar areas that are not served by motorcycle or tanker vendors (Nakwamekwi and Juluk). Our topics of discussion focused on their water supply situation and the role of water vendors.

We arranged the focus group discussions through the area chiefs, and we did not provide any compensation for their participation.

Analysis

We advance understanding of the structure of informal water markets by describing patterns of water vending associated with distributing water vendors securing water from the public water supply. First, our analysis examines the market structure in three steps: (1) describing flows of water and money; (2) mapping these money and water flows in relation to LOWASCO's piped water network; (3) assessing the market competitiveness and financial profitability of motorcycle water vendors. Second, we examine spatial patterns of water vending in terms of the location of water deliveries. The spatial data illustrate the potential value of our higher frequency data and information about the geographic coverage of water vendors (see also [38]. We describe the analytical approach below.

First, following Raina et al. [5], we describe the system of water supply in Lodwar by estimating the monthly water and money flows. We calculate the quantities of water supplied and revenue generated for both the water utility (LOWASCO) and water vendors. We use figures of quantities of water supplied and monthly revenue reported by LOWASCO, transaction logs from LOWASCO's central borehole (known as Moi Gardens) that supplies water vendors, our baseline surveys for sources, and tracking data from the boda boda and tanker truck vendors. We extrapolate figures from our random sample of motorcycle and tanker truck vendors (weighted based on stratification), but we are unable to do so for the private source vendors (such as private taps and boreholes) because we did not conduct a census of private taps and boreholes.

Second, we construct a map of water vending activity in relation to LOWASCO's piped water network. This allows us to better understand the relationship between informal and formal water supply. We map the deliveries in Lodwar using tracked customer delivery locations and quantities of water sold. The maps are overlaid with LOWASCO's piped water network to provide a visual comparison. We also conduct a few spatial analyses of hot spots: source prices per litre, customer prices per litre, and then the difference between customer price and source price per litre.

Finally, we examine the market competitiveness and financial profitability of vendors in Lodwar that use boda bodas to transport water (*boda bodas*). Following the methods used in Raina et al. [5], we use information from the baseline and high frequency surveys to approximate basic income statements for each vendor. We estimate each vendor's revenue; cost of goods sold (COGS); operating costs, or selling, general, and administrative costs (SG&A); and depreciation. We exclude interest and taxes, because these businesses are cash, informal, and pay very little in taxes. Only 10% of respondents reported borrowing money to purchase their motorcycle. This allows us to calculate financial metrics – gross margin, earned income before interest, taxes, depreciation, and amortization (EBITDA), and earned income before interest and taxes (EBIT). We use the financial metrics to assess profitability.

Boda bodas who rent their vehicle pay rental charges that are assumed to include depreciation and the vehicle owner's cost of capital. For the boda boda vendors who own their vehicles, we estimate the oportunity cost of capital and depreciation to allow comparison of profitability with those who rent.

Calculations for each vendor's revenue, COGS, SG&A, and depreciation differ slightly from Raina et al. (2019). To calculate revenue from water sales, we use the following equation:

$$Revenue = (P\_customer * N\_jerrycans + transport\_fee) \; * \; N\_trip \tag{1}$$

where $P\_customer$ is the price per 20L jerrycan paid by the customer; $N\_jerrycans$ is the number of jerrycans the vehicle can carry; $transport\_fee$ is the price that boda bodas charge to transport water. It is the price charged for the "most frequent trip [the vendor has] made in the last month transporting water." N_trips is the number of trips per week made from the source.

The COGS for the *boda bodas* includes the cost of water, the cost of fuel, and labour costs, calculated as:

$$cost\_water = (P\_source * N\_jerrycans) * N\_trips \quad (2)$$

$$cost\_fuel = N\_trips * 6km * \left(\frac{1L}{40km}\right) * \left(\frac{110KSH}{1L}\right) \quad (3)$$

$$cost\_labour = \frac{trips\_water}{trips\_total} * 280KSH/day * 6\ days \quad (4)$$

Where *P_source* is the price paid per jerrycan at the source (as a weekly average). To calculate the weekly cost of fuel, we make a few assumptions. Respondents were unable to give an estimate of the number of kilometres or the number of minutes the average trip took, so we use the most frequent trip's origin and destination as the length of the average trip (six kilometres for a return trip from a central staging location). We assume that the motorcycles used by the *boda bodas* have a fuel economy of 40 km/L of petrol. Average fuel prices during the study were 110 KSH/L.

Labour costs are difficult to assess in Lodwar because the *boda boda* vendors are one-person, owner-operator enterprises who do not pay themselves an explicit salary. We do not have an estimate for a daily wage rate in Lodwar. Instead, we use a wage rate of 280 KSH/day (US$2.80/day), as estimated by other studies conducted in rural and northern Kenya. Cook et al. [60] estimate a wage rate for unskilled manual labour in rural Kenya at 35 KSH/hr (US$0.35/hr), or 280 KSH/day (US$2.80/day) (assuming an eight-hour work day). Watete et al. [61] find that off-farm households in Northern Kenya earn an average of 75,000 KSH/year (US$750/year), or 288 KSH/day (US$2.88/day).

Boda bodas frequently also transport people and non-water goods. The methodology used to allocate shared costs can be "based on indicators such as sales, headcount or square footage depending on the nature of the cost" [62]. We choose to use number of trips – where the proportion of labour costs allocated to transporting water is based on its respective proportion of total trips taken. This is an important and strong assumption, especially with respect to capital costs. Allocating capital costs using this method may be incorrect depending on how vendors make the decision to transport water at the margin. For example, vendors who rent their motorcycles may consider the rental costs of their motorcycles as sunk costs, and they may view hauling water at the margin as a way to make a little extra money rather than sitting idle.

Boda boda operating costs, or SG&A, for transporting water are calculated using the following equation:

$$SGA\_water = \frac{trips\_water}{trips\_total} * (rent + repair + maintenance) \quad (5)$$

They incur little overhead and management costs as they are one-man, owner-operator models. A few spend small amounts on marketing – decals for their motorcycles or customized vests – but we do not include that in our calculations. We weight the SG&A costs by the proportion of trips for transporting water.

We use straight line depreciation for the boda boda vendor's major capital asset – the motorcycle. Similarly, we weight the depreciation cost by the proportion of trips for transporting water.

$$Depreciation = \frac{trips\_water}{trips\_total} * \frac{motorcycle\_cost}{motorcycle\_lifespan * 52} \quad (6)$$

Motorcycle_lifespan is measured in years, which respondents reported to be two. We divide the estimated market value of the (used) motorcycle by 104 to obtain an estimate of the weekly depreciation cost. A two-year estimated life of a motorcycle is much shorter than we had expected, given reports of five-year lifespans in other urban areas. Based on follow-up discussions with respondents, we attribute the short lifespan to the age (second-hand), low quality, and limited maintenance of motorcycles commonly used by vendors and intense usage carrying heavy loads on poor roads. We include sensitivity analysis for this assumption in the S1 Text, where we show profitability with a motorcycle lifespan of five years (S1 Text, Table A in S1 Text, Table B in S1 Text).

We assume the opportunity cost of capital for motorcycle vendors who own their vehicles is 12% (based on the yield of Kenya's 10-year Treasury bonds, which ranged from 11.5%-12.5% in 2018). This represents a lower bound for the opportunity cost of capital. We weight the opportunity cost of capital by the proportion of trips for transporting water. We also divide the interest by 52 to obtain a weekly opportunity cost of capital.

$$Opportunity\_cost\_capital = \frac{trips\_water}{trips\_total} * \frac{interest\_rate * motocycle\_cost}{52} \tag{7}$$

We calculate three profit measures: gross margin, EBITDA, and EBIT. Gross margin is revenue minus cost of goods sold. EBITDA is revenue minus COGS and SG&A while EBIT is revenue minus COGS, SG&A, and depreciation (See Raina et al. [5] for interpretation of different profit and profitability measures). We then calculate three key profitability metrics: gross margin ((revenue – direct product costs)/revenue), and operating margins (EBITDA/revenue and EBIT/revenue). We also calculate return on assets (EBITDA/average assets) for vendors who own their motorcycles.

Results

Water vendors in Lodwar

We find that informal vendors in Lodwar play an increasingly important role in water supply. Our interviews with key informants helped identify the drivers of the growth of the informal water sector. Water demand for domestic use and construction has increased due to the rapid population growth of the town due to devolution, the discovery of local oil resources, and subsequent increases in local business activity. The water system has failed to keep up with the growth in demand due to challenges faced by LOWASCO, including frequent breakdowns in the piped water system and disruptions due to drought and flooding. While the county government has two tanker trucks for use during emergencies (such as droughts), it contracts private vendors to supply water to schools, dispensaries, and villages. As a result, the number and role of vendors has increased substantially since 2013. The seasonal variation in vendors' sales has increased because of the important role they play in supplying water during droughts.

Tanker trucks and tractors are operated by many different types of institutional actors. We divide them into two categories – those that sell water and those that do not. Those that sell water include (1) individuals whose main source of income is selling water using tanker trucks or tractors, (2) larger businesses for which selling water is not a main source of income, (3) individuals working for a non-profit organization (NGO or school) who sell water themselves, and (4) non-profit organizations that sell water to support their main activities. Those that do not sell water include (1) the Ministry of Water, (2) NGOs that transport water for their own activities, and (3) private companies conducting corporate social responsibility activities (CSR).

Most of the tanker operators in our baseline sample began engaging in water-related activities in the last five years (69%), with 30% beginning in 2017. The barrier to entry is relatively high given the initial capital investment required. The average reported amount to start tanker operations is US$25,000 (median = US$18,000, sd = US$19,000). As a result, most operators in our sample (N = 9) report only owning one tanker truck or tractor (one has six, one has three, two have two). Tanker trucks have a mean capacity of 14,558L (sd = 8,529). Tractors are smaller and have a mean capacity of 5,000L (sd = 1,000). The average number of trips per day is 2.19 (sd = 1.4). Most make only one trip per day (52%), 19% make three trips per day, and another 19% make four trips per day. The average price to fill the tanker at the source is US$4.17/$m^3$ (sd = 0.96), and the average sale price is US$10.21/$m^3$ (sd = 1.39).

When tanker truck vendors were asked about the challenges faced, there was not one challenge that stood out. Two identified road quality and two identified payment delay by customers as their biggest challenges. Other challenges include the small number of sources, high prices at the source, not enough customers. With respect to desired policy changes, two wanted the number of sources (boreholes) to be increased, and two wanted the cost of water to be decreased.

As in many cities and towns across Kenya, motorcycle taxis are commonplace in Lodwar. Without a public transportation system, *boda bodas* are a dominant form of transport. The terrain is sandy and rocky, with few paved roads. Larger vehicles often cannot reach more remote households. The *boda bodas* wait together at "stages" for customers. The *boda bodas* will transport almost anything requested by the customer, from people and livestock to luggage, firewood, and water. From what we observed in the field and anecdotally from the drivers, those who choose to transport water tend to have older motorcycles or will do it for their long-time customers. Transporting jerrycans instead of people is harder on their motorcycle's shock absorbers, which need to replaced them more frequently.

Most of the *boda boda* drivers are young males, with an average age of 25. Eighty-six percent of the drivers are under the age of 30. Ten percent have no education, 40% have a primary school education, and 46% have a secondary school education. Thirty-nine percent did not have a job before becoming a *boda boda* driver, and 12% were casual labourers. The others have varying backgrounds – from shopkeeping, agriculture (farming, pastoralism, fishing) to being a barber or security guard. Most (81%) are from Turkana County, with 7% from Trans Nzoia and 4% from Uasin Gishu counties. A large majority are locals, from Lodwar Town (75%).

The business of using motorcycles to transport water has rapidly increased in the five years preceding the fieldwork. While 23% of the *boda bodas* began transporting water before 2014, 30% began in 2014 and 2015, 24% began in 2016 alone. However, the growth of *boda bodas* transporting water declined in 2017 and 2018 – with 15% and 8% of *boda boda* vendors beginning in those years. Since 2018, there has been a sustained drought in the Horn of Africa, including in Lodwar.

About half of the *boda boda* drivers own their motorcycle (48%) and the other half rents the motorcycle for 500 KSH per day (or US$5/day, with only three drivers reporting lower prices). When we asked drivers that rent by the day about the owner of the motorcycle, the responses were all different – there was no evidence of a prolific owner of motorcycles. Those who owned their motorcycles, on average, paid US$900 (median of US$950, sd = US$213) for their motorcycle. Nineteen percent of the owners borrowed money to pay for the motorcycle. We did not collect interest information from these owners; we use a proxy instead to calculate the opportunity costs of capital. The *boda bodas* spend an average of US$17/week on petrol (sd = 9). The drivers report a mean cost of US$9 each time (sd = 7) each time their motorcycle was serviced, with an average of 2.5 service trips per month (sd = 1.11). When multiplied, we get a monthly service cost of US$24 (sd = 21). With respect to large repairs in the last year, the mean reported cost was US$72 (sd = 68).

In general, the sales model of the *boda boda* vendors is similar to that of transporting people or other goods. The customer tells the *boda boda* driver that they would like to purchase water (usually four jerrycans) from either a private tap (for drinking) or the river (for construction). The *boda boda* driver then fetches the money (for the water) and the jerrycans from the household. The price for four jerry cans of water is usually US$0.20 (at US$0.05/20 L jerrycan). The *boda boda* driver is paid the transport fee separately, usually US$1.00 or US$1.50, depending on the distance travelled.

In contrast with the tankers for whom no single challenge stood out, for the boda bodas road quality was by far the largest and most common complaint (45%), followed by a lack of customers (21%), and too few water sources (11%). We also asked them about the policy changes they would like to see. Their most frequent response was to increase the number of boreholes (31%), followed by improving road quality (21%), improving piped water network coverage (18%), and increasing number of outlets at the source to reduce waiting time (10%).

Role of vending in supplying Lodwar's water

Fig 1 illustrates the money-water flows for the town of Lodwar (see S1 Text). We extrapolate from our sample for all vendor types except private taps; we did not conduct a census of private taps. Drawing on our survey data, we estimate that LOWASCO produces 210,694 m^3 of water per month and receives US$51,140 per month (or an overall revenue of US$0.24/$m^3$). These estimates compare with production estimates from a recent water service delivery planning study (2022) of 6,353 m^3/day from all supply boreholes (i.e., 190,590m^3 over a 30-day period) [63]. An external audit of LOWASCO identified US$68,750 in revenue [64]. In terms of water sales, we estimate that 2,910 m^3 of water per month is sold at the main borehole. Based on a price of US$5/$m^3$, LOWASCO receives US$14,550 per month for this water.

We divide the sales of water into two types – to tankers that do not sell water (1,786 m^3) and tankers that do (1,124 m^3). From our sample of tankers that sell water, we estimate from the tracked data sale volumes of 700 m^3/month with revenues of US$7,630/month (or US$10.90/m^3). From our sample of tankers that (generally) do not sell water, we estimate sale volumes of 2,841 m^3/month with revenues of US$1,450/month (or US$0.51/m^3). We observe a discrepancy between the estimated volumes and logged purchases at the source for the tankers that do not sell water. Based on enumerator feedback, we suspect this is partly due to the organizations timing their transport to our monitoring despite randomization of day observed. In other words, the vendors wanted to show us their water trips on the days we were monitoring to make it worthwhile.

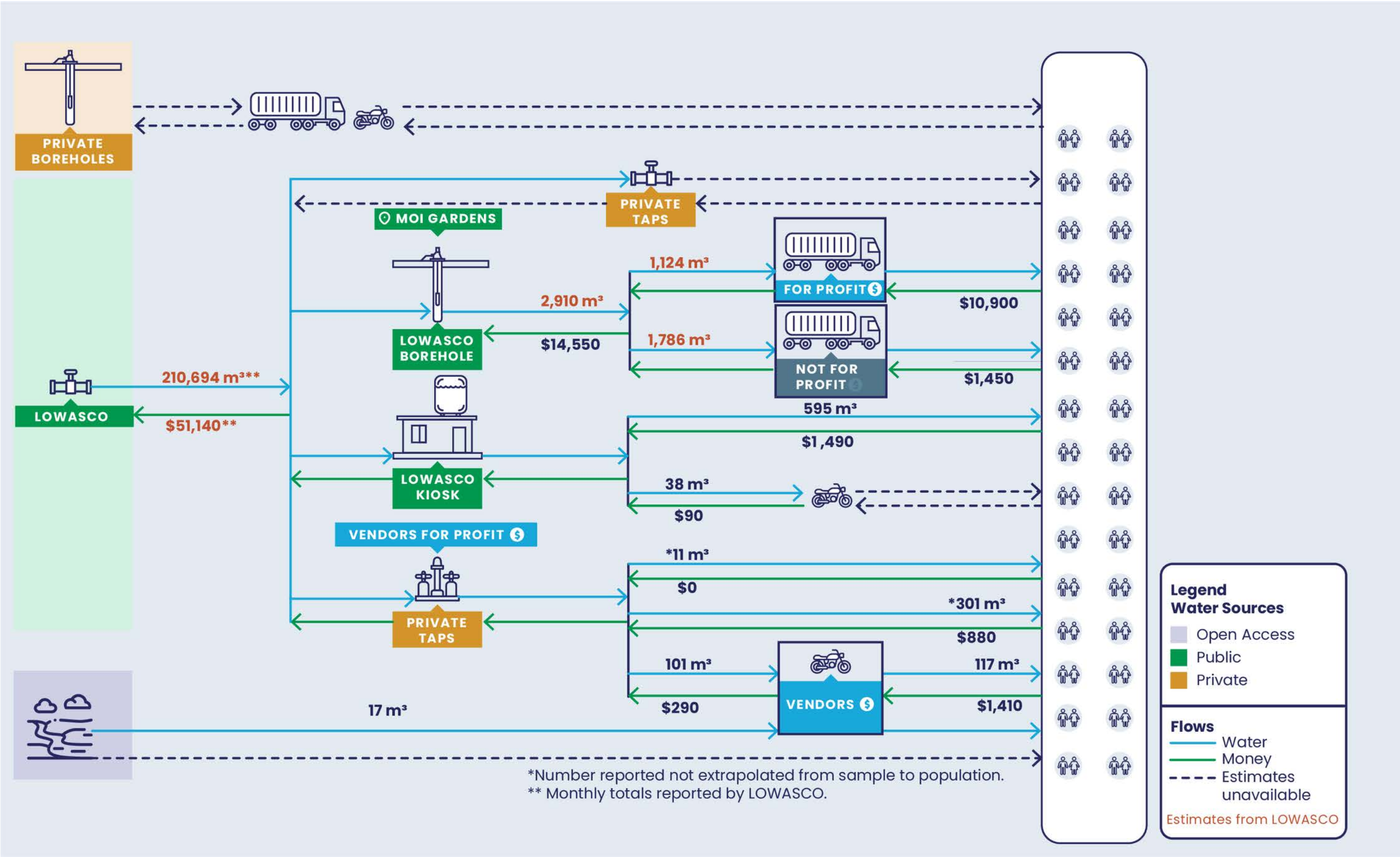

Fig 1. Monthly Water and Money Flows in Lodwar (June 2018).

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From the data collected from respondents with private taps, we calculate monthly volumes and revenues (for our sample only – not extrapolated for Lodwar). They provide 11 m^3 free water to individuals each month and sell 301 m^3 to individuals coming to fetch water for a revenue of US$880. This comes to an average sale price of US$2.91/$m^3$, which is consistent with common reports of a price of US$0.05 per 20L jerrycan – sometimes US$0.10 per 20L jerrycan.

Extrapolated for all of Lodwar, motorcycle vendors purchase 101 m^3/month from private taps for US$290/month (purchase price of US$2.91/$m^3$). They obtain 17 m^3/ month from the river for free. In total, they sell 117 m^3 for US$1,410/month. The average sale price is US$12/$m^3$, slightly higher but still comparable to the unit sale price of tanker water.

LOWASCO also provides water for communities through non-automated water kiosks. Of a total of 32 kiosks, there were 11 functional kiosks at the time of the study. Six automated water kiosks (known as "water ATMs") are located in the "internally displaced persons" (IDP) camp south of Kanamkemer. At the time of the study, there were five operational manager-operated water kiosks – with two north of the "central business district" (CBD), two in Nakwamekwi (west of the CBD), and one in Napetet (north east of the CBD). None of the non-automated kiosks north of the River Kawalase and south of the River Turkwel in Kanamkemer and Nawoitorong were operational.

From our interviews of kiosk managers, we find that together, four of the five kiosks were providing 595 m^3/month to the surrounding households, charging a price of US$2.50/$m^3$ (or US$0.05/jerrycan) and receiving revenues of US$1,488/month. Vendors rarely purchase water from these kiosks, instead choosing to purchase from vendors with private taps. One of the five kiosks reported selling to people on motorcycles (not necessarily vendors). This kiosk reported about 38.4 m^3 per month sold for a total revenue of US$96/month.

We do not have estimates for the amount of water households collect from either boreholes or the river. However, we understand from our focus group discussions and field observations that these sources are important parts of the water supply, especially for households that are not connected to the piped water system. In Fig 1, flows to and from these sources are depicted using dashed lines.

Figs 2–4 shows the spatial structure of the water vending market. We mapped the tracked water deliveries and overlay them with LOWASCO's piped water network to provide a visual comparison [65]. There is significant overlap between areas of concern for piped water and vended water deliveries. As expected, many deliveries occur outside the piped water coverage area (assumed to be a 2km buffer from LOWASCO pipes). However, we also find hotspots of water deliveries in areas within 2km of the water network. Much of these deliveries can be explained by the overlay illustrating household concerns for the quality and/or reliability of the piped drinking water. Most of the deliveries occur in areas of high concern. The few exceptions can be explained by the tanker truck deliveries to institutions and construction sites within areas of low concern.

Most of the *boda boda* deliveries are made across the River Kawalase toward the north of Lodwar. This area exists mostly outside piped network services. Many of the households living in this area were resettled there because they were displaced by either floods or the construction of internally displaced people (IDP) camps in the southern part of Lodwar. There used to be some piped water access and kiosks in this area (as illustrated by the network map), but floods in 2016 washed away a critical segment of the pipes (FGD #3; 2018). Since then, there has not been any water in the pipes in this area, and households have turned to fetching water from the River Kawalase, collecting from private taps across the river, or purchasing water from *boda boda* vendors (FGD #3,7, 8; 2018). With respect to tanker deliveries, we see many in the southern part of town, in Kanamkemer. While a majority of deliveries clearly fall outside of the piped water network, many deliveries are still within the coverage area of the pipes. Most of these customers are large institutions (universities, organizations) or wealthier households that can afford to use an alternative source.

Profitability of boda bodas

Table 1 presents the weekly profits in USD of *boda bodas* in Lodwar who own their motorcycles. Table 2 presents the same information for *boda bodas* who rent their vehicles. The tables show our estimates of revenue, cost of goods sold, fixed costs, and depreciation and present income statement estimates for gross margin, EBITDA, and EBIT.

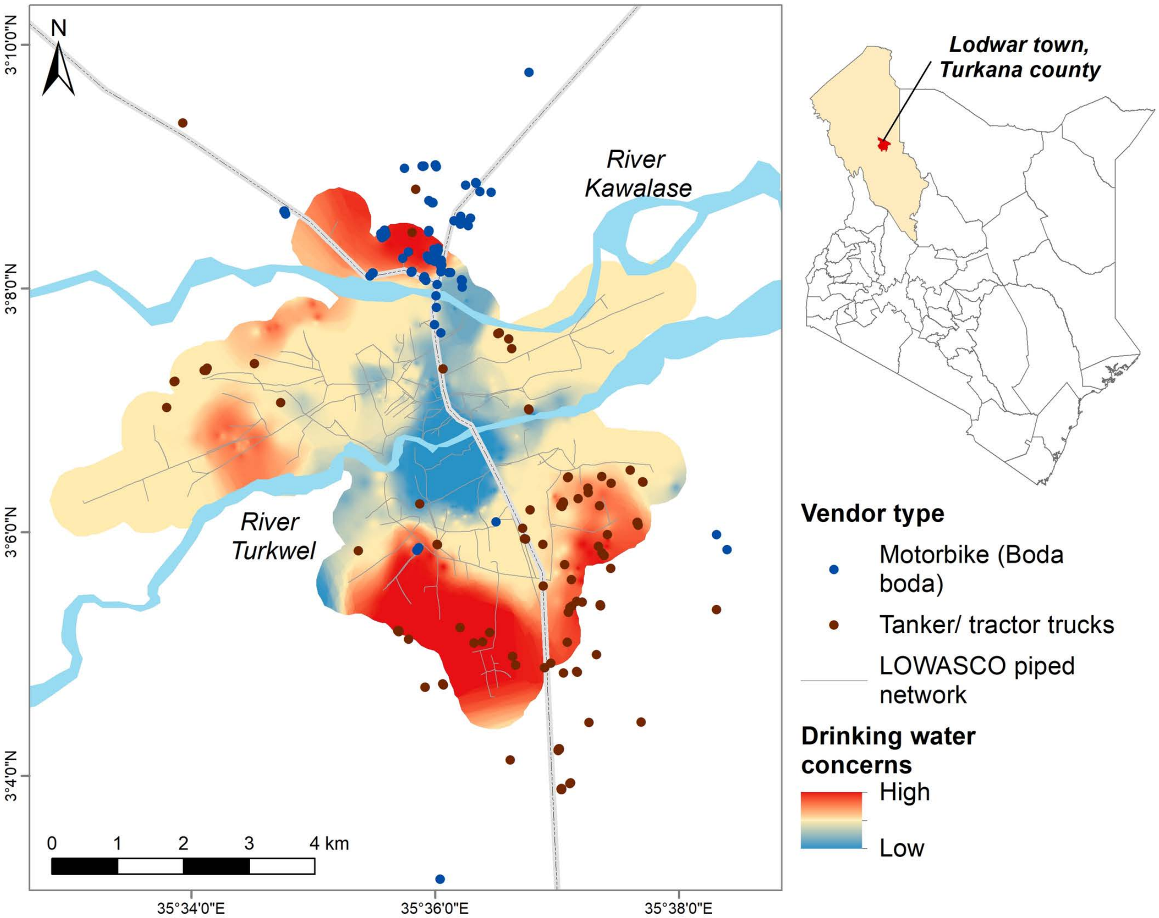

Fig 2. Location of water deliveries by vendor types and network coverage. *Data on drinking water concerns were collected through a household survey (n = 909) in October 2017. The heatmap shown is generated through Optimised Hotspot Analysis of reported scores (0 = Low and 3 = High concerns) followed by Inverse Distance Weightage interpolation in ArcGIS 10.8.*

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Equipment costs represent a significant portion of overall costs. While renters pay for these capital costs in the rental payment to the vehicle owners, vendors who own their motorcycle incur these capital costs in the depreciation of their vehicle and the opportunity cost of the capital invested. EBITDA for renters therefore includes the renters' cost of capital. EBITDA for owners does not. EBIT for owners includes depreciation, but it does not include the opportunity cost of capital. Therefore, EBITDA for renters is not comparable to EBITDA for owners or EBIT for owners.

Overall, owners generate more revenue from transporting water than do renters (US$20.60 vs. US$12.10) largely because the proportion of water trips for owners is 0.41, while the proportion of water trips for renters is 0.23. The motorcycle owners' cost of goods sold is similarly nearly double that of renters (US$14.97 vs. US$8.84). This reflects that owners are transporting more water than the renters. They spend similar amounts on maintenance and repairs (US$2.08 by owners vs. US$2.12 by renters). Renters are responsible for minor repairs and regular maintenance. The cost of the motorcycle (aggressively depreciated over two years) for the owners is about half of the rental cost of the motorcycle for renters (US$3.65 vs. US$7.03 for the rental). The opportunity cost of capital for owners averages US$0.88 and has a median of US$0.79. The combined depreciation and opportunity cost of capital for owners is US$4.53, less than that of renters (US$7.03). This difference suggests that our estimate of the opportunity cost of capital for owners is probably too low.

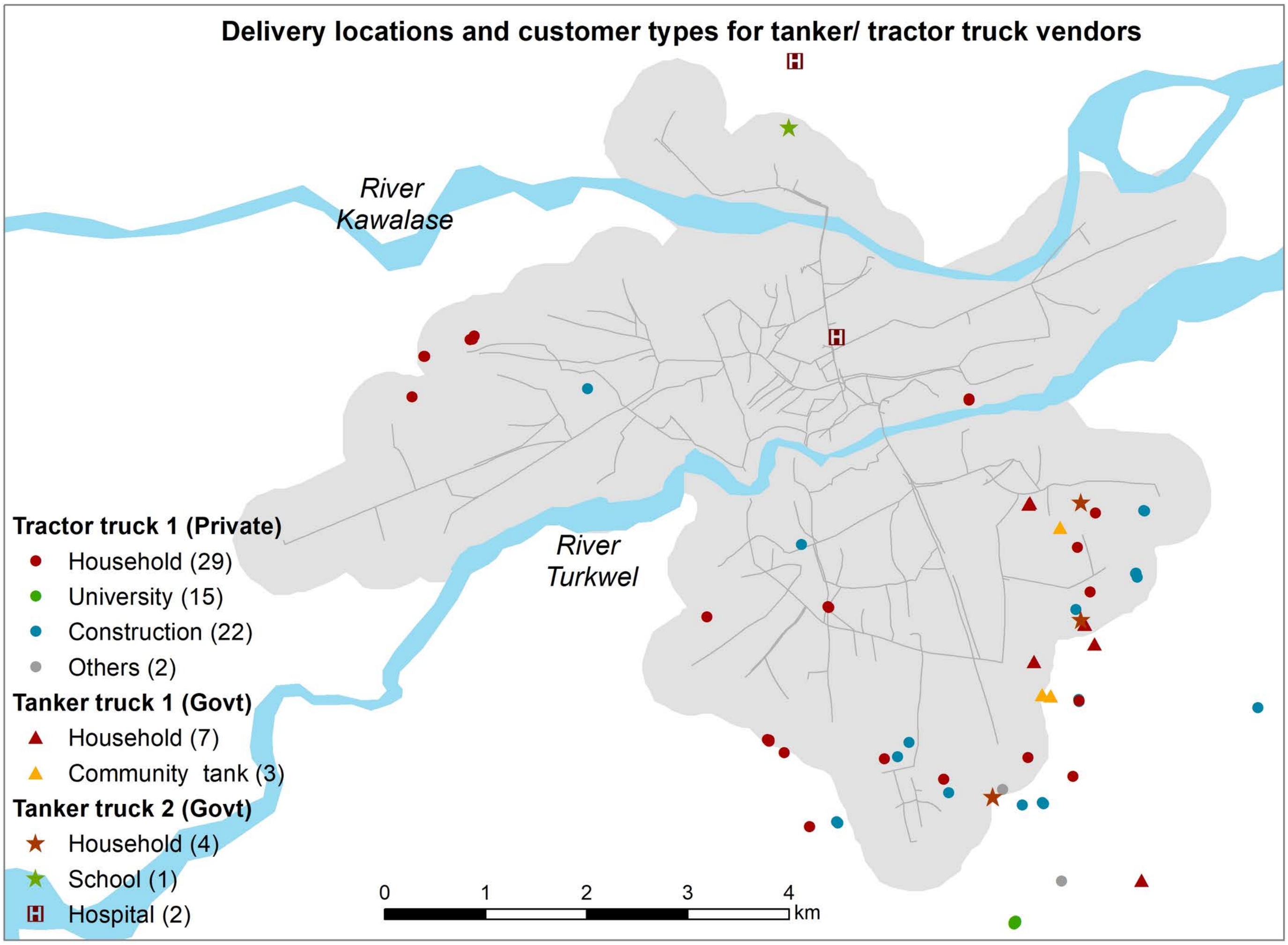

Fig 3. Delivery locations and customer types for tanker/ tractor truck vendors.

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Based on our assumptions, boda bodas appear to lose money transporting water, as reflected by the renters' EBIT and owners' EBIT after subtracting the opportunity cost of capital. EBIT for the owners averages -US$0.97, while EBIT for renters averages -US$5.98. The median *boda boda* that rents his motorcycle loses US$3.29/week transporting water, while the median *boda boda* that owns his motorcycle loses US$1.18/week transporting water.

When examining profitability (Table 3), we find that renters compared to owners have similar gross margins (mean of 0.29 vs. 0.26, respectively). The positive gross margin shows that water vendors are earning enough from sales to cover the costs of goods sold (i.e., cost of water, labor, and fuel related to water transport). However, gross margin in a capital intensive business does not accurately portray profitability because the costs of capital are not included.

Water vending is an asset heavy business, and capital allocation decisions limit the usefulness of comparing operating margin profitability ratios. Given this caveat, we find that owners have a negative operating margin -0.04 (EBIT/revenue), and renters have a negative average operating margin of -0.44. This means that the vendors are losing money on their core operations after accounting for its direct costs and operating expenses, suggesting that the water vending business is not sustainable in their current form. The return on assets for owners is also negative.

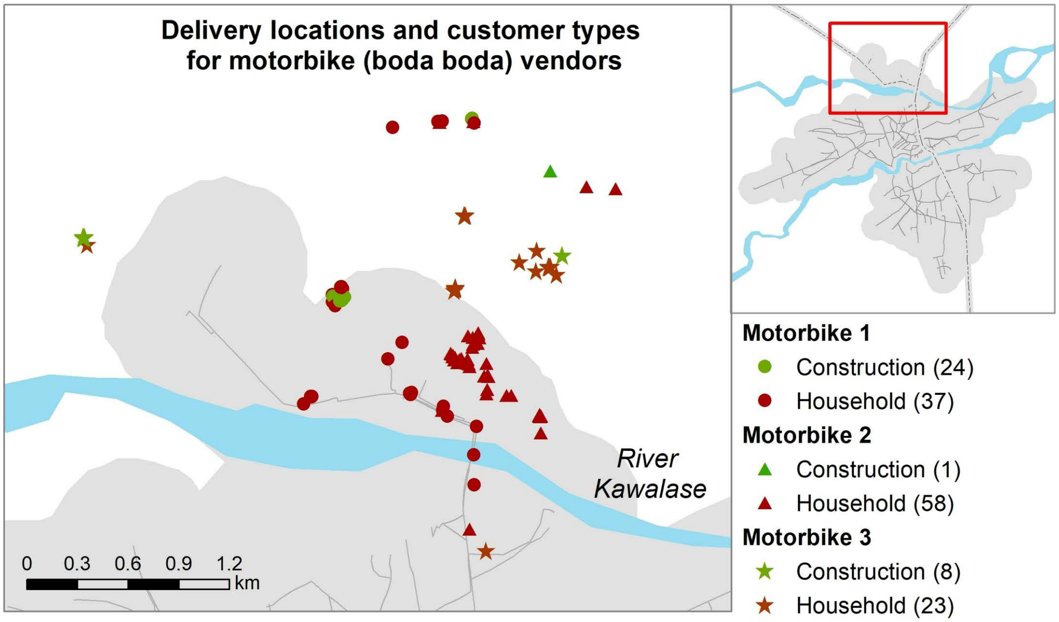

Fig 4. Delivery locations and customer types for motorbike (boda boda) vendors.

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Table 1. Profits from transporting water of boda bodas who own motorcycles (USD, per week).

	N	Mean	SD	P10	Median	P90
Revenue	7	20.60	13.68	5.40	22.00	39.20
Cost of goods sold	7	14.97	10.18	4.65	13.82	29.82
Labour costs	7	6.90	5.45	1.75	4.98	14.00
Product costs	7	5.57	4.94	0.00	4.00	13.20
Supply chain costs	7	2.50	1.81	0.50	2.64	4.62
Gross margin	7	5.63	3.89	0.76	7.65	9.54
Selling, general, and administrative costs	7	2.08	1.48	0.44	1.71	4.22
Maintenance and repairs	7	2.08	1.48	0.44	1.71	4.22
Equipment rental	7	0.00	0.00	0.00	0.00	0.00
EBITDA	7	3.56	3.43	-0.37	3.43	7.83
Depreciation	7	3.65	2.70	0.65	3.30	7.21
EBIT	7	-0.09	2.18	-1.88	-1.03	4.00

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Our findings rely on our assumption that vendors allocate capital costs proportionally to their water business. In the case that vendors consider transporting water as a marginal business where capital costs are zero, gross margin would be the most meaningful indicator of profitability.

Discussion

Mixed provision of water in Lodwar

We find a complex set of institutional arrangements in the provision of water supply in Lodwar, with many different actors, of which some are “formal” and others “informal”: the local water utility, Turkana’s County government, local and

Table 2. Profits from transporting water of boda bodas who rent motorcycles (USD, per week).

	N	Mean	SD	P10	Median	P90
Revenue	10	12.10	9.64	3.00	9.00	26.80
Cost of goods sold	10	8.84	8.29	1.36	8.09	22.41
Labour costs	10	3.94	4.32	0.78	2.35	10.97
Product costs	10	3.53	4.34	0.00	1.60	10.80
Supply chain costs	10	1.37	1.09	0.33	0.99	3.05
Gross margin	10	3.26	3.03	-0.32	2.93	7.71
Selling, general, and administrative costs	10	9.16	10.25	1.61	4.83	25.16
Maintenance and repairs	10	2.12	2.85	0.18	0.62	7.27
Equipment rental	10	7.03	7.72	1.40	4.20	19.58
EBITDA	10	-5.89	9.82	-21.39	-3.29	3.10
Depreciation	10	0.00	0.00	0.00	0.00	0.00
EBIT	10	-5.89	9.82	-21.39	-3.29	3.10

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Table 3. Profitability of *boda bodas* from transporting water.

	N	Mean	SD	10th percentile	Median	90th percentile
Owners						
Gross margin (gross margin/revenue)	7	0.26	0.08	0.14	0.24	0.37
Operating margin (EBITDA/revenue)	7	0.13	0.15	-0.07	0.14	0.33
Operating margin (EBIT/revenue)	7	-0.04	0.14	-0.24	-0.05	0.18
Return on assets (EBIT/average assets)	7	-0.12	0.48	-0.79	-0.12	0.61
Renters						
Gross margin (gross margin/revenue)	10	0.29	0.25	0.00	0.24	0.63
Operating margin (EBITDA/revenue)	10	-0.44	0.53	-1.10	-0.52	0.29

Note: EBITDA for owners and renters are not directly comparable because full capital costs are included for renters but not for owners.

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international NGOs, a local church, international corporations, and small private enterprises. The structure of water supply systems uncovered in Lodwar challenges the simplistic dichotomy of formal and informal water provision [30,66]. The various actors play complementary and overlapping roles in Lodwar's water supply. We find evidence of this through institutional arrangements, as well as financial and spatial relationships.

LOWASCO and the water vendors have a complex relationship. LOWASCO and a subset of water vendors have a formal relationship, where LOWASCO allows registered tanker truck and tractor vendors to only purchase from LOWASCO's main borehole at Moi Gardens, in downtown Lodwar (We identified another source used frequently by tanker trucks and tractors, but this was an illegal source and vendors that used this source declined to participate in our study). We find that LOWASCO and the water vendors have an important financial relationship. We estimate LOWASCO's revenue from their central borehole (Moi Garden) to be 28% of the utility's overall revenue from all operations, making source sales to vendors a critical utility operation. Furthermore, the utility costs of collecting fees from vendors are much lower, with collections from metered households much more challenging and delinquent according to key informant interviews. LOWASCO has monopoly control of raw water sources for tanker truck and tractor vendors. Private sale of raw water to tanker truck and tractor vendors is not permitted. LOWASCO and the county government set the prices at the borehole, at US$5.00/$m^3$. *Boda bodas* also indirectly purchase water from LOWASCO, through private taps and kiosks.

In addition to the extensive financial overlap between LOWASCO and the water vendors, we also find evidence of some spatial overlap. Our spatial analysis supports existing literature on water vendors (1) supplementing utility service provision within the boundaries of the piped water network [7,66–69]and (2) serving those "outside the reach of the utility," particularly in peri-urban areas [66,70,71]. However, our findings diverge from the existing work in two ways. First, we also find many customers served by tanker vendors that live within the service area of the piped network. They are institutions and wealthy households, who often can afford to connect to the piped water network but instead choose not to. Second, we also find vendor activity in peri-urban areas. However, our findings challenge researchers to re-examine the meaning of "outside the reach of the utility." We identify one peri-urban community that previously had access to piped water, but due to a lack of resources to repair a large break caused by floods, no longer had water flowing through the pipes. This narrative diverges from much of the literature – the initial, expensive capital outlays have been made, but for various reasons, households turn to vended water to fill the gap.

Lodwar's case demonstrates that the relationships and scope of activities of the state's formal water supply and water vendors is dynamic and varies over time. Lodwar's water supply is especially vulnerable to climate shocks – with droughts and floods shaping how the government and water utility relate to water vendors. During periods of drought, the county government will hire water vendors with tanker trucks and tractors to supply Lodwar town and its surrounding areas. For example, the drought in 2017/8 led to a two-month government contract for water vendors.

Our observational data of water vending in Lodwar provides additional evidence that there is high variability in vendor and state activity on a day-to-day basis. For example, the Ministry of Water's tanker trucks would be inactive for weeks due to a breakdown and lack of funds to make repairs. Vendor tanker trucks and tractors would also experience long periods of inactivity. Through interviews and reports from the field, we found that water vending activity would adapt to demand in Lodwar in two ways. First, the use of tractors in Lodwar allows for flexibility – when demand for water is low, the tractors are used on farms to generate income. Second, vendors would migrate to other towns in Turkana or nearby cities that faced higher demand for vended water. It is unclear how efficiently capital is being utilized in Lodwar.

The Catholic Church, international NGOs and corporations also play an important role in supplying Lodwar's water. The existing literature focuses on two main actors – water vendors and the utility – and neglects the role of other actors in water supply. Lodwar presents an interesting case, with non-governmental, organizational actors playing a greater role in water supply, in addition to their participation in the water vending sector. For example, UNICEF, OXFAM, and World Vision drill and equip boreholes for LOWASCO, as well as smaller communities outside Lodwar. UNICEF also constructed water kiosks within Lodwar. Save the Children provides chlorine for water treatment from four boreholes and also assists with water quality testing as LOWASCO and governmental bodies do not have the facilities to do so. The Catholic Church runs pump maintenance teams that repair boreholes and handpumps in Lodwar and surrounding areas. Many of these NGOs and corporations will also purchase large storage tanks for communities and then deliver water using their own tanker trucks during periods of high need. In addition to their capital investments and operational and maintenance expenditures, these non-governmental organizations also participate in institutional strengthening and policy-making. UNICEF participates in regular WASH and county steering meetings.

Profitability and competitiveness of boda boda water vendors

Our profitability analysis shows that the *boda boda* water vending is a difficult, capital-intensive business. For the average *boda boda*, their net income is close to zero or negative, showing that (1) many vending operations are not profitable and (2) the water vending market is likely a commoditized and competitive market. There are three explanations for why vendors may continue to transport and sell water.

First, we assume that if the business owner is a rational economic actor, they would not continue to operate a money losing business. The largest expense is the fixed cost of renting, or depreciation of, the motorcycle. This has two implications. First, the *boda boda* drivers need to carry out as much revenue-generating activity as possible after having incurred the cost of the motorcycle. The gross margin from transporting water is generally positive (i.e., the marginal revenue is higher than the marginal cost), which is why they continue to carry out this activity. They likely carry water when they are waiting around for customers. Second, other non-water activities would need to be more profitable, because the *boda bodas* need to cover the shortfalls in order for EBIT to be positive. This is especially true for those who rent their motorcycles, as transporting water is on average EBIT negative but makes up a smaller proportion of their overall business.

Second, our analysis is sensitive to two assumptions about labour and capital costs. First, labour costs make up a significant portion of the costs of goods sold. While we assume the labour costs are equal to the wage rate for unskilled off-farm, manual labour, net income is sensitive to this assumption. (Recall that labour costs are on average US$5.16/week while EBIT is -US$3.51/week.) It is unclear how owner-operators conceptualize their labour costs, as they do not explicitly pay themselves a wage. In models describing entrepreneur decision-making, the wage rate (opportunity cost) is only one input – other important components include the individual's own ability, access to capital, risk aversion, and existing assets [72]. Owner-operators may accept a lower wage rate due to the benefits of having a more flexible work arrangement [73]. In studies that estimate income from driving for ride-sharing apps, researchers do not bound labour costs, instead choosing to subtract costs from revenue and then discuss the difference as the wage rate [74,75]. In effect, they assume net income (i.e., EBIT) is zero. In the short-run, there may also be owner-operators who do not fully internalize all of the costs and may eventually exit after realizing that revenues do not cover their costs. This could result in high turnover in drivers, similar to that seen in the ride-hailing industry [75].

If the *boda bodas* are willing to accept a lower wage rate than that for unskilled, off-farm, manual labour, the net income (EBIT) calculated in this exercise could be positive for the average motorcycle owner. For renters, however, even if labour costs were zero, net income would still be negative (-US$1.95/week) for the water portion of the business. Given the labour market context in Lodwar, it is not implausible that *boda bodas* may accept a lower wage rate. Unemployment rates are high in Lodwar and the surrounding region, as shown by the 39% of *boda boda* drivers who did not have a job before. Additionally, many expressed anxiety and stress about having enough business to pay the rental rate and to purchase food.

Our assumptions around capital costs also affect the interpretation of profitability for *boda bodas*. While our main analysis assumes a relatively short lifespan of two years for the motorcycles, we conduct a sensitivity analysis using a lifespan of five years in S1 Text, Table A in S1 Text, Table B in S1 Text. Net income as measured by EBIT is positive for motorcycle owners, at US$2.10/week and US$2.83/week for lifespans of five and ten years, respectively. Furthermore, operating margins all become positive, though not statistically significantly different from zero. Return on assets remains the same – at zero.

Finally, vendors may continue to transport water at a loss if simple concepts of profitability are not able to capture the full picture when assessing water vendors. Their operation may indicate that there are widespread inefficiencies in labour and capital allocation. Water vendors in Lodwar may not necessarily be driven by profit and loss; the informal market may be serving other purposes. For example, capital investments could be used as a savings mechanism. However, assessing the plausibility of this explanation is beyond the scope of our paper.

In comparing the water vending market in Lodwar to that in Kathmandu (Raina et al., 2019), we find similarities between the *boda bodas* who own their motorcycles in Lodwar and the tanker truck vendors in the dry season in Kathmandu. The close financial ratios indicate that water vending markets are similar across countries (gross margin of 0.26 in Lodwar and 0.23 in Kathmandu, EBITDA operating margin of 0.13 in Lodwar and 0.10 in Kathmandu) [5]. Both markets are highly competitive, with many price-taking firms, a commoditized product, low barriers to entry, and no evidence of supernormal firm profits. The operational and financial structure of water vendors is also similar, with heavy reliance on capital assets, relatively cheap labour, and water that is not differentiated by quality.

Implications for policy and practice

Our study offers spatial monitoring methods and suggestive evidence to inform decision-making by four interrelated types of actors: vendors, consumers, utilities, and regulators. There are vendors of many different types relying on public versus private water sources, a wide range of consumers varying by income and type (e.g., households versus businesses or institutional consumers), and utilities with different service areas, infrastructures, and capacities. Ample experience in the informal sectors of low-income economies highlights the need for caution and humility in making policy recommendations, so our discussion of implications focuses on suggestive evidence emerging from Lodwar as well as ways that spatial monitoring methods can inform key decisions in other similar contexts. With these caveats in mind, we explore implications for each actor below with reference to selected business decisions, consumer empowerment initiatives, water service delivery planning, and regulatory reforms. In each case, the focus is harnessing the potential benefits generated by mobile vending whilst addressing access, affordability, and quality concerns.

For vendors, the study and its core methodological innovations can help better understand finances and the viability of water vending as a livelihood option, particularly as steps are taken to address the major externalities of vending and to integrate vendors into public service delivery where appropriate. Better accounting and financial literacy for vendors can make these operations more viable by identifying ways of cutting costs (e.g., optimising distances travelled) or expanding co-benefits (delivering free or subsidized water from public clients). Understanding why some vendors are operating at a loss is a priority for future research. In competitive marketplaces where vendors lack market power, reduced costs can be passed on to consumers. At the same time, utilities that enrol vendors as extensions of piped water networks can account for financial realities in performance-based contracts and take steps to reduce the costs of water distribution (such as access to public sources closer to consumers). The spatial data about mobile water deliveries can help vendors identify neighbourhoods and businesses in greatest need and can highlight to utilities and regulators where and how vendors serve different consumers and communities during expansion efforts or disruptions. Spatial monitoring can support recognition of vendors and can help the vendors professionalize, form associations, or otherwise self-regulate. In so doing, opportunities to lower operating costs can allow vendors and the utility to jointly achieve socially optimal levels of water access.

For consumers, vendors serve schools, places of worship and other facilities where the poor have access. Widespread access to spatial monitoring data can empower consumers and has potential to build transparency about the sources, prices, and reputation of vendors (including their timeliness and whether the water they sell makes consumers sick). For such benefits to become accessible to those most in need, mobile phone platforms or other public forums for information about vendors is necessary. Access to such phones has penetrated even some of the poorest communities. This potential has been recognized by social enterprises and venture capital in the East African context, exemplified by PowWater (Power of Water, www.powwater.com), which has received over US$5 million (2024) from a range of funders (e.g., Gates Foundation, overseas development assistance, private capital) to create "a mobile platform for ordering and delivering quality-tested clean water to both households and businesses in Nairobi, Kenya" [76]. Spatial monitoring can support diverse consumers by making such platforms part of public water service delivery accessible beyond the wealthiest consumers. Institutional consumers of vended water (health care facilities, places of worship, schools) are a particular priority for accessing such information as they are most likely to have the capacity to access such resources and the potential to secure water that benefits the poor.

For the water utilities and regulators, the study and its methods can inform several decision-making processes: water service delivery planning, registration of vendors and enforcement of vending guidelines, and different forms of public-private partnerships, such as contracting to respond to droughts and disruptions. In terms of water service delivery planning, our study illustrates two important roles of vendors: they both overlap and extend the piped water network. The spatial data highlights the opportunities to account for water vendors in terms of source management (e.g., making public sources at the periphery more accessible to vendors to reduce travel time and costs), bulk water charges to vendors (who are required to pay relatively high bulk water rates, that are passed onto consumers in competitive marketplaces), and in terms of the associated utility revenues from water vendors. Spatial data on hot spots of water vending can help utilities identify priorities for investment in piped water networks and the associated need for effective engagement with vendors.

Beyond water service delivery planning, our study and its spatial data has implications for ongoing efforts to engage vendors and regulate and monitor them according to the WASREB Guideline on Water Vending (hereafter "the

Guideline"). The Guideline sets as an objective "to regulate the quality of water supplied to citizens by all actors beyond the utilities directly regulated by WASREB [77]." The limited evidence about vended water quality suggests that contamination often occurs during transport or after delivery, although in some situations vendor purification practices have yielded a cleaner alternative than the treated water from utilities [2,27]. At the heart of the Guideline are efforts to make water vendors visible and accountable, requiring high frequency, low-cost, and spatially explicit data on water volumes, prices, and quality. For regulators, the Guideline calls for a database of vendors, registered by utilities, and consumer protections for water quality and tariffs. For utilities, it stipulates the need to inventory vendors, manage water sources, harmonize tariffs, and spot check quality. For vendors, the aim is to support self-regulation and professionalization. Here utilities and other public bodies face a conundrum due to the same capacity constraints that limit public provision in the first place. Spatial data that has value to for all actors, and is relatively low-cost to collect and visualize can build trust and accountability in a blended model of public service delivery. Doing so is easier said than done, however, and must include plans to navigate the up-front practical and political resistance.

Coming back to Lodwar's specific circumstances, water vending plays an important role in water supply that is influencing the municipality's water development path. Vendors are active where there is inadequate piped water supply and where households can afford to pay them, generating a high-revenue water supply that accounts for a disproportionately large share of revenue for a struggling utility. An inventory of vendors and an understanding of their service areas and delivery patterns can play an important role in coordinating the piped water and vended water networks as they develop. These insights come with limitations, however. We are limited in our ability to address several important questions. For example, we do not know if the water utility is less likely to repair piped water supply issues if households have other means of water supply, including vended water. However, our FGD participants indicated that this is unlikely. As another example, the question of whether vendors are a temporary or permanent fixture remains unanswered, although limited progress in expanding services since our 2018 field season (confirmed by the WASREB's annual Impact report and our follow up interviews with key informants) suggests vendors are unlikely to go away soon. It seems likely that policymakers can shape this outcome, as widespread, difficult-to-reverse, private investments have not yet been made in the water vending system. Household storage tanks are not yet common, and vendor capital investments in tanker trucks and motorcycles can be used for other purposes, or in other locations. Finally, it is unclear under which conditions wealthier households and institutions that are currently using vended water would switch to purchasing from the water utility.

Conclusion

Our paper makes three major contributions. First, we find that there is a mixed water system in Lodwar, and informal vendors play an important role in water supply. Second, we demonstrate the value of monitoring informal water vending activity in this context. Monitoring can motivate increased engagement between informal water vendors and formal water providers. Additionally, the information gathered can support evidence-based management and policy interventions. Finally, we identify the practical challenges and strategies for monitoring vendors that can be used by practitioners and other researchers.

We contribute to an understanding of water supply in rapidly growing towns and small cities and the structure of informal water markets as it relates to the formal water supply system. As one of a few studies to document an urban, informal water market structure, we illustrate the rich landscape of institutional actors responsible for supplying water to households, schools, churches, hospitals, construction sites under conditions of extreme climate variability and vulnerability. We find that informal water vendors complement the formal, public water system, as well as other non-profit actors. We delve into the relationship between the formal and informal water supply sectors, finding that a substantial portion of the city's water is provided by vendors both within and outside the piped water service area. The water vendors are adaptive, increasing service during times of water need and easily switching to other, non-water services. Water vending provides an important source of employment for young males in Lodwar.

Second, we demonstrate the importance of monitoring water vending. We identify how the informal water sector relates to the formal, public water sector. We find overlap and complementarity in both our spatial and financial analyses. Our monitoring data can be used to support evidence-based investment planning or regulations. We also demonstrate the value of monitoring over time – we find that vending activity in Lodwar varies over time. These data will become important as efforts to implement the Guideline on Water Vending increase, raising important questions about how registered versus unregistered vendors behave (although data on the latter will prove particularly hard to capture). Continued monitoring is needed to answer questions around seasonality and climate shocks, as well as information about how motorcycle vendors combine water sales with their other deliveries. Our work shows the potential value of supporting water vending observatories underpinned by cross-sectional, long-term monitoring to inform communities of research and practice.

The act of monitoring itself comes with additional benefits, such as increased engagement between the various sector actors. In particular, the water utility and the vendors can more easily share information, increase mutual understanding, and engender trust. Monitoring, if done well, can serve as the basis for deeper public engagement, such as contracting and regulation, as well as support public health outcomes by integrating water quality testing. This could include licensing or tariff subsidies.

With respect to feasibility of monitoring water vendors, we demonstrate proof of concept of using GPS tracking of informal water vendors to capture high-resolution, longitudinal monitoring of spatial and temporal patterns. Vendors in Lodwar were willing to participate in longer term GPS tracking with low-cost devices. Informal vendors in Lodwar often welcomed confidential profitability assessments and spatial maps of their deliveries. However, there remain challenges with participation from vendors who are nervous about revealing their business practices – both to competitors and to city authorities. Vendors that take from unsanctioned sources are challenging to engage. Consideration of the ethics and desirability for monitoring needs to be a priority for both sector actors and especially researchers.

Finally, our study in Lodwar illustrates the importance and challenges of water vending. Not only does water vending provide access to households and institutions that need water beyond that supplied by the city, but it may also provide sources of employment and income. There remain important policy questions around efficient capital allocation and labour market challenges that we leave for future research. Finally, vending touches on fundamental policy debates about how to deliver water services, and questions remain about the compatibility of profit-seeking vendors and the public interest. Our study offers data, methods, and insights that bring empirical evidence to consider when utilities and regulators consider whether and how to integrate small-scale, off-grid, and often private distribution options.

Supporting information

S1 Text.
(PDF)

S2 Text.
(DOCX)

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