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Water flows, energy demand, and market analysis of the informal water sector in Kisumu, Kenya

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Abstract

In rapidly growing urban areas of developing countries, infrastructure has not been able to cope with population growth. Informal water businesses fulfill unmet water supply needs, yet little is understood about this sector. This paper presents data gathered from quantitative interviews with informal water business operators (n=260) in Kisumu, Kenya, collected during the dry season. Sales volume, location, resource use, and cost were analyzed by using material flow accounting and spatial analysis tools. Estimates show that over 76% of the city's water is consumed by less than 10% of the population who have water piped into their dwellings. The remainder of the population relies on a combination of water sources, including water purchased directly from kiosks (1.5 million m^3 per day) and delivered by hand-drawn water-carts (0.75 million m^3 per day). Energy audits were performed to compare energy use among various water sources in the city. Water delivery by truck is the highest per cubic meter energy demand (35 MJ/m^3), while the city's tap water has the highest energy use overall (21,000 MJ/day). We group kiosks by neighborhood and compare sales volume and cost with neighborhood-level population data. Contrary to popular belief, we do not find evidence of price gouging; the lowest prices are charged in the highest-demand low-income area. We also see that the informal sector is sensitive to demand, as the number of private boreholes that serve as community water collection points are much larger where demand is greatest.

Keywords

Informal water sector; Water flows; Developing countries; Water market analysis; Water demand

1. Introduction

Access to safe water is increasingly recognized as a basic human right (Meier et al., 2012), especially in light of the high disease risks associated with unsafe water and sanitation access (Pruss et al., 2002). Yet, access to safe water sources remains a significant problem in many rapidly-growing cities in developing countries, as infrastructure is often unable to cope with unprecedented urban population growth (WHO and UNICEF, 2012). Although

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access to improved water sources has increased in Asia to meet the Millennium Development Goals, this is not the case in sub-Saharan Africa, where only 61% of the population has improved water access (WHO and UNICEF, 2012). The problem is especially acute in rapidly urbanizing regions, where the rate of urban expansion exceeds those of economic growth and infrastructure development (Gulyani et al., 2005). As a result, many people turn to informal water services, such as small-scale water vendors and bottled water delivery, for their drinking water (Sima and Elimelech, 2011). Studies show that more than 25% of the population in Latin American cities and 50% of the population in African cities depend on the informal water sector (Solo, 1999a). In Kenya, only 14% of urban households have private connections (Kenya Open Data Project, 2012). Interruption of services as a result of unreliable electricity, over-utilized systems, and leaks undermine services for even those with private connections (Gulyani et al., 2005). Furthermore, negative or low pressure which results from intermittent piped water supplies contributes to recontamination of treated water (Geldreich, 1996; Kumpel and Nelson, 2011). Research has shown that the small-scale private sector has been estimated to account for 85% of all private-sector investment in water security (Kariuki and Schwartz, 2005).

Regardless of distribution mode or treatment technology, the supply of high-quality drinking water can carry a high environmental burden. Treatment via conventional means has been shown to produce 300 g of CO_2 equivalent per cubic meter of water treated (Vince et al., 2008a). Even more alarming, especially in cities with aging piped distribution systems, are the high energy and monetary costs associated with pumping water (Colombo and Karney, 2002; Filion et al., 2004; Hertsin et al., 2011; Vince et al., 2008b). Life cycle impacts for municipal water treatment and distribution (Lundin and Morrison, 2002; Mohapatra, 2002; Stokes and Horvath, 2005) and for water bottle distribution (Larson and Larson, 2006) have been investigated previously, but little is known about the impact of *informal* water supply systems. Estimating such impacts first requires a thorough understanding of water supply networks, but this presents a difficult logistical challenge due to the lack of regulation or registration of nontraditional supply mechanisms. Considering the rate of growth within the informal water sector and its prominent role in water supply in developing cities, it is of paramount importance to better understand the sector, including its environmental impacts.

Access to sufficient volumes of safe drinking water is an important means to curtailing the spread of waterborne and water-associated diseases and reducing child mortality (Montgomery and Elimelech, 2007). Understanding of the informal water services sector is crucial to curtail the spread of waterborne diseases, manage resource use, and improve services in any municipality where the sector plays an important role. Unlike rural water and sanitation interventions where sustainability metrics have been presented previously (Montgomery et al., 2009), there exist no objective measures of sustainability for urban informal systems. Due to the unregulated and often illegal character of the sector, information is difficult to gather. To date, over 10,000 water businesses have been documented in 49 countries, but very few published studies are quantitative or comparative in nature (Solo, 1999a).

In studying the informal sector in Kisumu, our purpose is to quantify resource flows in the informal system, and examine spatial variation in pricing, demand, and water source. We compare resource use in the informal sector to the conventional municipal sector, and use census data to gain a better understanding of spatial variation in the informal sector. While it is outside of the scope of this study to create a precise mass-balance of all water used in the city, we did seek to a statistically significant sample within the city to credibly compare the scale of energy use and pricing across different water provision types and locations. Furthermore, the data gathering and analysis techniques presented here could be used by city planners to understand the sector in other areas where it plays a prominent role.

2. Methodological and Ideological Options

2.1. Study Site

With an official population of nearly one million (2009 Kenyan Census), Kisumu, which is located on the banks of Lake Victoria (Fig. 1) has grown by 80% in the previous decade (Kenya Bureau of Statistics, 1999). Water shortages have been reported in Kisumu since the 1980s (KIWASCO, 2007). KIWASCO, the Kisumu Integrated Water and Sewerage Company, a semi-private company and municipal water provider, reports that the water demand was nearly three times greater than production capacity in 2007 (KIWASCO, 2007). By 2007, only 36% of the city's population had service coverage (Schwartz and Sanga, 2010). As a result, the majority of the city's population lacks a sufficient quantity of water for uses such as cooking and cleaning (Wagah et al., 2010).

2.2. Data Collection

Preliminary data collection occurred in July and August of 2008 and 2009. Data were gathered by using a "bottom-up" approach, (Whittington et al., 1991) through direct interviews with operators. After a series of open-ended interviews, we defined a set of standard interview questions to collect data from the heads of large water companies and municipal water managers. Questions were structured, but also open-ended, allowing for natural conversation.

Water kiosk operators, water baggie vendors, and water cart vendors were each asked a survey translated to Kiswahili and back-translated to English for accuracy. Four native Swahili-speaking enumerators carried out these surveys. Selection of kiosks operators for inclusion was not randomized; we interviewed operators at nearly all kiosks in the city. Water cart vendors were interviewed as they collected water at one of the kiosks. The location of all kiosks was recorded by using eTrex handheld GPS devices. Water baggie vendors were surveyed as they worked at the market and bus depot.

In addition, we collected data about bottled water sales in the city. A standardized survey translated to Kiswahili was used to collect data from wholesale bottled water distributors, small grocery stores, street peddlers, and other small shops. Sales data from the largest supermarkets and bottled water vendors in the city were supplied voluntarily to the principal investigator after detailed conversations about the project.

We collected water demand data from 2008 to 2009 from the municipal water provider, KIWASCO. Demographic information for each neighborhood was obtained from the 1999 (World Resources Institute, 1999) and 2009 (Kenya Open Data Project, 2012) Kenyan census.

2.3. Measures

All interviews were used to gather data about average water sales volume(s) of the particular company/person, source of water, cost to acquire water, price charged to consumer, and the use of resources, including electricity and chemicals for treatment. In addition, we gathered information from companies that utilized motorized vehicle transportation on weekly distances driven and fuel efficiency of vehicle fleets. Data collected from the municipality included the number of public and private connections in each area of the city, the total volume of water sold to each area, and the mean energy consumption for pumping throughout the city. Census data were grouped by neighborhood within the city. We utilized measures of water source and sanitation use by each resident in 2009 (Kenya Open Data Project, 2012). Population density growth was examined by subtracting 1999 (Kenya Bureau

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of Statistics, 1999; World Resources Institute, 1999) density from 2009 density (Kenya Open Data Project, 2012).

3. Data Analysis

3.1. Material Flow Analysis

Information from all interviews was combined to calculate a flow analysis and energy use profile for various sectors in the water sector. Material flow analysis is a data analysis tool of industrial ecology and has been previously employed for the assessment of various environmental issues in developing countries (Binder et al., 1997; Giljum, 2004; Streicher-Porte et al., 2005). It uses mass balance principles to create a model of the stocks and flows of a resource or resources through a bounded system. As such, it can be applied at different scales, ranging from individual industrial processes to cities to entire national economies (Fischer-Kowalski and Huttler, 2008). At larger scales, material flow analysis normally relies on high-quality aggregated datasets, prepared by municipal or higher-level authorities. Such data are hard to come by in developing areas, mostly due to a lack of funding. Most importantly, by their very nature, the activities and impacts of the informal water services sector are not included in such governmental studies. STAN, a software that supports such analysis with consideration to data uncertainties, was used to aggregate and analyze data collected from interviews (Cencic and Rechberger, 2008).

In order to calculate cumulative energy demand (Hirst, 1974; Huijbregts et al., 2010), we first defined boundaries. We consider extraction of water from the environment (e.g., river or groundwater) to delivery to the household. We do not account for wastewater discharges because the informal system does not deal with wastewater directly. The design of the system of flows is based on information acquired in interviews, and verified by results of survey data. Although stock-and-flow diagrams are used, water is not stored by any of these intermediary agents (or is stored for a comparatively short amount of time) and we are concerned primarily with flow of resources. We combined data from municipal databases, aggregated estimates based on operator responses to survey questions, and water bottle distributor sales records to calculate water flows among different parts of the informal water sector.

Cumulative energy demand is calculated by using similar methods for both the municipal and the private water treatment plant. In both cases, we consider the use of chemicals, energy to operate the plants, and replacement of degrading pipes (for the municipal system), as well as the average monthly water output by each. For the Nyamasaria private water treatment plant, we were supplied with the average monthly use of diesel to run an incoming water pump, chemicals to treat water (aluminum sulfate, sodium carbonate, calcium hypochlorite), and electricity use by the operators from their records. For the municipal system, we collected information on chemical use, electricity use, and pipe construction over time. We computed energy required to produce chemicals to operate the plants by multiplying the primary energy equivalent (the energy necessary for mining, transporting, and manufacturing the chemical) of each chemical, available from literature, (Hellstrom, 1997; Lundin et al., 2000) with estimated material use from interviews. Fuel use and electricity were each multiplied by the energy requirements to produce each energy source. Specifically, the primary energy for the production of electricity in Kenya was drawn from the International Energy Agency's non-OECD Country energy balance database, (International Energy Agency (IEA), 2010) while that for the production of diesel fuel used to operate water pumps was drawn from the ecoinvent life cycle inventory database (Ecoinvent, 2010) Embodied energy associated with routine maintenance to the piped municipal system was calculated by using the previous year's replacement rates, combined with an estimate of energy required for the replacement of piped water conduits (which

takes into account materials used as well as construction) (Ecoinvent, 2010). We assume energy used during construction of the water treatment plants to be negligible in comparison to the energy required to operate plants during their lifetime, as was shown for water infrastructure elsewhere, (Mo et al., 2010) and do not calculate this energy use.

The use of resources by trucks for the entire sector (four trucks) was estimated by using information provided by one business owner who supplied 50% of the market. We were given information about average monthly sales for the previous year (of which we took an average), as well as monthly petroleum expenditures. We assumed that majority of the resource use would be accounted for by fuel combustion, as has been previously demonstrated for the freight industry in the US (Facanha and Horvath, 2006). Thus, we use fuel use as a proxy for cumulative energy demands of trucking. Primary energy for diesel production is computed by using databases described above (Ecoinvent, 2010).

3.2. Spatial and Statistical Analyses of Kiosk Data

Data were entered into and analyzed by using SPSS Version 19.0 (IBM, Armonk, NY). The grouping of spatial information from interviews to neighborhood locations was completed with the use of ArcGIS 9.10 (Esri Software, Redlands, CA). Census data from smaller “sublocations” were aggregated into larger neighborhoods to allow for qualitative comparison with kiosk response data (see Fig. 1 for final locations). Spatial joining was used to combine data collected from interviews with water kiosk operators to five neighborhoods within the city. Data from five areas of the city, including pricing and sales volume, are compared by using the F-test in analysis of variance. Frequencies of different kiosk source water within the city are compared between neighborhoods by using the Fisher's test. Pricing and demand of kiosks that extract water from different sources (tap water or groundwater) were compared by using the two-tailed t-test.

4. Results

4.1. Types of Water Services

Several types of water businesses are identified in Kisumu. A private small-scale water treatment plant, Nyamasaria, operates outside of town. Two water truck companies collect water from this private treatment plant and deliver it to consumers. Water kiosks are collection points where consumers refill containers; they provide water from city taps or boreholes. Water cart vendors are laborers that deliver containers filled with water to individual households. They charge per container and collect empty containers when delivering filled ones. Bottled water is sold by large grocery stores, wholesalers, small shops, and street vendors. Water baggie vendors fill small plastic bags with water and sell these at public spaces such as the market. Two hundred and forty-five kiosks were identified in Kisumu.

4.2. Mass Flow of Water Sales in Kisumu

The majority of volumetric water flows in the city are conventional — treated municipal water is delivered to the private taps of registered households. Indeed, less than 25% of the total accounted-for-flow was delivered to users via informal services (Fig. 2). Although the volume of water flowing in the informal sector is only a minor fraction of total water flow in the city, the majority of city residents rely on this water. Fig. 3 shows the percent of households that use various water sources. As this figure demonstrates, the informal sector is supplying more than 50% of households in Kisumu (Wagah et al., 2010).

Water flow in the informal sector is presented in Fig. 4. As anticipated, the largest flow is that of water sold at kiosks that supply over 600 m^3 of potable water per day. The majority

of the water sold at kiosks comes from municipal tap water (548 m^3/day), while a smaller number supplied directly from groundwater via boreholes (109 m^3/day). Notably, a small private water treatment plant in a peri-urban area, Nyamasaria, supplies nearly as much water (365 m^3/day) as all of the kiosks combined. Although the largest amount of water from both kiosks (403 m^3/day) and the private water treatment plant (160 m^3/day) is sold directly to households living in the vicinity of the facility, a significant portion of water from kiosks (173 m^3/day) and the private water treatment plant (105 m^3/day) is also sold to water cart vendors who push wooden carts to transport water to other areas of the city. These vendors, in turn, sell the majority of their water to individual households (201 m^3/day) as well as small businesses (77 m^3/day). Surprisingly, relatively little water (120 m^3/day) is transported via trucks.

4.3. Cumulative Energy Demand

Cumulative energy demand is analyzed for each water supply mode. Total daily energy demand is higher for municipal treatment and pump stations than other water provision means (Fig. 5). This includes life-cycle energy equivalent for the chemicals used in water treatment, energy used to treat water, and energy used to pump water to households. Trucks, which transport less than 1% of the total water in the city, use nearly 20% the energy of the entire municipal system. Scaling energy demand to the volume of water produced (i.e., MJ/m^3), makes it apparent that the transport of water by trucks around town is the least resource-efficient means of water delivery. Even the Nyamasaria treatment plant is inefficient in comparison to the municipality, possibly as a result of efficiencies of scale. Inefficiencies in the trucking sector were anticipated prior to analysis, but the scale of inefficiency is surprising. Parallel systems for the rich and poor will greatly exacerbate resource use within cities overall, while increasing the socioeconomic divide in urban areas.

4.4. Spatial Analysis of Kiosk Data

Table 1 summarizes data describing kiosks by neighborhood within the city. There are significant neighborhood-by-neighborhood differences in price paid for water from kiosks (pb0.001), water source for kiosks ($p=0.019$), and type of kiosk operator ($p=0.042$). Table 2 summarizes neighborhood-level census results, including population density, population growth, water source of residents, and sanitation coverage within each area. Manyatta, an unplanned development, has the highest population density (15,500 persons/km^2) and the largest rate of growth (3640 more persons/km^2 than the previous decade). Southern neighborhood, on the other hand, has the lowest population density (1780 persons/km^2), and has actually seen a decline in the rate of population growth (310 less persons/km^2 than the previous decade).

Water prices at kiosks are highly variable among different areas in Kisumu (variance 25.10, range 1–40 Kenyan Shillings/20 L container). Price charged does differ significantly among the neighborhoods ($p<0.001$), but the largest prices are not found in the areas with a high demand, as measured by length of line waiting to refill water at a kiosk (Table 1), population density or rate of population growth (Table 2). Rather, price seems to be the highest in areas where consumers can afford to pay larger fees. In the central market area, most consumers are small businesses, and the prices charged here are much higher than elsewhere.

The length of lines at various kiosks can be used to approximate demand, assuming that the filling rate is similar among locations. Lines are longest in Manyatta, which is the neighborhood with the largest population density, population growth, and lack of piped water from the municipality (Wagah et al., 2010). The surrounding neighborhood, Nyawita-Migosi, which has the second-largest population density (Table 2), also suffers from longer lines (Table 1). In these areas, KIWASCO has struggled to provide adequate pressure to the

tap-water kiosks (KIWASCO, 2007). Based on census data, these are also the areas with large percentage use of water cart vendors and ground water sources for drinking (Table 2).

There is no clear relationship between the source of water sold at kiosks and pricing. A comparison of water pricing at kiosks that sell treated municipal water and those that sell groundwater from boreholes (Table 3) shows no clear price trends across neighborhoods. In one area, Kaloleni-Northern, kiosks selling from groundwater are actually charging significantly more ($p=0.03$) than those selling municipal water. Municipal water is treated and considered to be of greater quality, so price differences may be characteristic of location of the types of kiosks in this area, rather than of a preferential valuation of borehole water. There is also a lack of trends when considering the length of line (a proxy for demand) between kiosks selling municipal tap or ground water (Table 3).

5. Discussion

We demonstrate that data can be gathered, and triangulated, from a variety of sources to describe informal water businesses. Although the informal water sector accounts for only 25% of the total water flows within the city, it is responsible for supplying over 50% of the population with their primary water sources. The importance of the informal sector has been recognized by other sources (Whittington et al., 1991; Zuin et al., 2011), but this article adds to the literature by quantifying this volumetrically, rather than in regard to percentage of the population served alone. By using material flow analysis, we show that over 30% of the total water (200 m^3/day) from kiosks being transported by hand-drawn water carts, nearly five times is the volume transported by water trucks (45 m^3/day). This most likely reflects Kisumu's current level of development. Past studies have shown that, in Latin America, operators prefer trucks to donkey-drawn-carts as urban areas have developed (Solo, 1999a).

Water treatment and distribution in the informal sector is associated with a larger energy demand per volume of water. For water treatment, the small private Nyamasaria plant is inefficient in comparison to the municipality, likely because it operates intermittently and is unable to take advantage of efficiencies of scale. Inefficiencies in the trucking sector (in comparison to piped systems delivery) were anticipated prior to analysis, but the scale of inefficiency is larger than anticipated likely as a result of irregular demand and routes. We are unable to quantify energy use by hand-drawn carts or boreholes as these both rely on human labor. Currently, this human-labor dependent water provision is most significant in the informal sector, but we can anticipate that, as has happened in Latin American cities, (Solo, 1999a) economic development will increase the prevalence of trucking. Water truck delivery is the most energy-intensive form of water delivery in the city. The municipal system is currently the largest energy user-per-day in the water sector, but continued growth in Kisumu, if not matched by infrastructure investment, is likely to exacerbate resource use in the city by increasing dependence on energy-intensive trucking.

We demonstrate that spatial analysis is a useful means of analyzing variability in informal water kiosk pricing and demand. Other studies have suggested that walking distance – a significant contributor to time spent gathering water (Zuin et al., 2011) – is an important factor in the decision to purchase water from one source over another (Alcorn et al., 2011; Mu et al., 1990). Further, a recent study has shown the link between walking distance and health in sub-Saharan Africa (Pickering and Davis, 2012). Nonetheless, we are unaware of other studies that have examined the relationship between location and prices charged by kiosks. In Kisumu, we find that water prices vary significantly by neighborhood within the city. Furthermore, we show that prices are not demand-sensitive because water is not most expensive where demand (measured as average length of lines) is highest. Rather, the largest prices are charged in to businesses in the central market area and in the wealthier Southern

neighborhood, reflecting the ability of consumers to pay in each neighborhood. This finding contradicts conventional opinion that private providers take advantage of poor urban residents (Solo, 1999a). Instead, we find that, in neighborhoods with the highest demand, private boreholes are more likely to sell water as kiosks. Other spatial studies of kiosk pricing would be necessary to verify the universality of these findings in other areas.

We find that households purchasing from the informal sector in Kisumu use less water per-capita than households with formal utility connections. Although we noticed that water for cleaning or washing was being collected from stagnant ponds or the lake, our interviewees did not offer any additional sources of water for cooking and drinking for which we did not account. This was confirmed by the household survey data in Kisumu collected during the same time period (Wagah et al., 2010). In Nairobi, Kenya an end-user study in informal settlements con-firmed that urban water use per capita has decreased by more than 25% over the past 40 years, with the decrease attributable to the rise in the percentage of households that rely on informal door-to-door water vendors (Gulyani et al., 2005). Informal operators are vilified in many areas because there is a fear that low-income consumers will economize water use since they are charged much higher per-volume fees than wealthier families with utility connections (Solo, 1999b). Per-capita water consumption below certain levels is not recommended as it may increase the likelihood of disease transmission due to insufficient resources for hygiene and drinking (Gleick, 1996; Howard and Bartram, 2003; World Bank, 2004).

It is worth noting that in Kisumu, Kenya, during the time of the study, a neighborhood delegated management approach was implemented in the Nyalenda neighborhood (Schwartz and Sanga, 2010). Based on our data, Nyalenda was the unplanned development neighborhood with the lowest kiosk prices and shortest lines. Legalization and regulation of informal water businesses have been recommended as a way to minimize the negative externalities of informal water services (Sima and Elimelech, 2011; Zuin et al., 2011) in other contexts. Neighborhood-level price and demand data and analysis, as presented in this paper, could aid in designing regulations for the informal sector.

We faced several limitations in analyzing this data. Although human labor is undeniably a significant form of energy used in Kisumu's informal sector, we did not include it in cumulative energy demand calculations. As such, we were unable to compare energy use of water delivered via hand-drawn carts with water delivered via pipes or trucks. Furthermore, we discuss trends and similarities between neighborhood-level water kiosk and census data, but we cannot demonstrate statistical significance in these associations due to the small number of neighborhoods (n=5) in Kisumu. Finally, data was collected during the dry season, and may not be representative of the wet season.

6. Conclusion

Bottom-up data collection and analysis are useful tools for understanding the informal water sector. This sector relies heavily on human labor in Kisumu, although the largest non-renewable energy expenditure is that of water delivery by truck. In Kisumu, we do not find evidence that prices are exploitative, and find, to the contrary, that they are responsive to the ability to pay of consumers. Nonetheless, per unit, water is more expensive when purchased from the informal sector than when provided directly by the municipality during the dry season. Parallel systems for the rich and poor will greatly exacerbate resource use within cities overall, while increasing the socioeconomic divide in urban areas. The informal water sector is meeting a need unmet by the municipality, but in a less resource-efficient and more expensive way.

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References

Alcorn T, Opryszko M, Schwab K. Formative ethnographic research to improve the evaluation of a novel water system in Ghana. American Journal of Tropical Medicine and Hygiene. 2011; 84:801–805. [PubMed: 21540392]

Binder C, Schertenleib R, Diaz J, Bader HP, Baccini P. Regional water balance as a tool for water management in developing countries. International Journal of Water Resources Development. 1997; 13:5–20.

Cencic, O.; Rechberger, H. Material flow analysis with software STAN.. In: Verlag, S., editor. Environmental Informatics and Industrial Ecology. Lüneburg: 2008.

Colombo AF, Karney BW. Energy and costs of leaky pipes: toward comprehensive picture. Journal of Water Resources Planning and Management. 2002; 128:441–451.

Ecoinvent. Ecoinvent Life Cycle Inventory Database v2.2. Swiss Center for Life Cycle Inventories; 2010.

Facanha C, Horvath A. Environmental assessment of freight transportation in the US. The International Journal of Life Cycle Assessment. 2006; 11:236–247.

Filion YR, MacLean HL, Karney BW. Life-cycle energy analysis of a water distribution system. Journal of Infrastructure Systems. 2004; 10:120–130.

Fischer-Kowalski M, Huttler W. Society's metabolism: the intellectual history of materials flow analysis, part II, 1970–1998. Journal of Industrial Ecology. 2008; 2:107–136.

Geldreich, E. Microbial Quality of Water Supply in Distribution Systems. Lewis Publishers; Boca Raton: 1996.

Giljum S. Trade, materials flows, and economic development in the south: the example of Chile. Journal of Industrial Ecology. 2004; 8:241–261.

Gleick PH. Basic water requirements for human activities: meeting basic needs. Water International. 1996; 21(2):83–92.

Gulyani S, Talukdar D, Kariuki RM. Universal (non)service? Water markets, household demand and the poor in Urban Kenya. Urban Studies. 2005; 42

Hellstrom D. An energy analysis for a wastewater treatment plant: an estimation of physical resources. Water Environmental Research. 1997; 69:44–51.

Hertsin LM, Filon YR, Hall KR. Evaluating the environmental impacts of water distribution systems by using EIO-LCA-based multi-objective optimization. Journal of Water Resource Planning and Management. 2011; 137:162–172.

Hirst E. Food-related energy requirements. Science. 1974; 184:134–138. [PubMed: 17791434]

Howard, G.; Bartram, J. Domestic Water Quantity, Service, Level and Health. World Health Organization; Geneva, Switzerland: 2003.

Huijbregts MAJ, Hellweg S, Frischknecht R, Hendriks HWM, Hungerbuhler K, Hendriks AJ. Cumulative energy demand as predictor for the environmental burden of commodity production. Environmental Science and Technology. 2010; 44:2189–2196. [PubMed: 20108964]

International Energy Agency (IEA). Energy Balances of Non-OECD Countries. Organization for Economic Co-operation and Development (OECD); 2010.

Kariuki M, Schwartz J. Small-scale private service providers of water supply and electricity. 2005 World Bank Policy Research Working Paper, 3727.

Kenya Bureau of Statistics. Population Figures for Towns and Municipalities. Republic of Kenya; 1999.

Kenya Open Data Project. 2009 Kenyan Census. 2012.

KIWASCO. Kisumu Water and Sewerage Company Strategic Plan 2007–2012. 2007.

Kumpel, E.; Nelson, K. Impact of Water Quality of Conversion from Intermittent to Continuous Water Supply in Urban South India, Water and Health: Where Science Meets Policy. University of North Carolina; Chapel Hill, NC: 2011.

Larson, A.; Larson, J. Bottled Water: Pouring Resources Down the Drain Earth Policy Institute Report. 2006.

Lundin M, Morrison GM. A life cycle assessment based procedure for development of environmental sustainability indicators for urban water systems. Urban Water. 2002; 4:145–152.

Lundin M, Bengtosson M, Molander S. Life cycle assessment of wastewater systems: influence of system boundaries and scale on calculated environmental loads. Environmental Science and Technology. 2000; 34:180–186.

Meier, B.; Kayser, G.; Amjad, U.; Bartram, J. Implementing an Evolving Human Right Through Water and Sanitation Policy. 2012.

Mo W, Nasiri F, Eckelman MJ, Zhang Q, Zimmerman JB. Measuring the embodied energy in drinking water supply systems: a case study in the Great Lakes Region. Environmental Science and Technology. 2010; 44:9516–9521. [PubMed: 21105699]

Mohapatra PK. Improving eco-efficiency of Amsterdam water supply: a LCA approach. Journal of Water Supply Resources Technology: Aqua. 2002; 51:217–227.

Montgomery M, Elimelech M. Water and sanitation in developing countries: including health in the equation. Environmental Science and Technology. 2007; 41

Montgomery M, Bartram J, Elimelech M. Increasing functional sustainability of water and sanitation supplies in rural sub-Saharan Africa. Environmental Engineering Science. 2009; 26:1017–1023.

Mu X, Whittington D, Briscoe J. Modeling village water demand behavior: a discrete choice approach. Water Resources Research. 1990; 26:521–529.

Pickering AJ, Davis J. Freshwater availability and water fetching distance affect child health in sub-Saharan Africa. Environmental Science and Technology. 2012; 46:2391–2397. [PubMed: 22242546]

Pruss A, Kay D, Fewtrell L, Bartram J. Estimating the burden of disease from water, sanitation, and hygiene at a global level. Environmental Health Perspectives. 2002; 110:537–542. [PubMed: 12003760]

Schwartz K, Sanga A. Partnerships between utilities and small-scale providers: delegated management in Kisumu, Kenya. Physics and Chemistry of the Earth. 2010; 25:765–771.

Sima, L.; Elimelech, M. Informal small-scale water services in developing countries: the business of water for those without formal municipal connections.. In: Selendy, J., editor. Water and Sanitation Related Diseases and the Environment: Challenges, Interventions, and Preventative Measures. Wiley International; 2011.

Solo TM. Small-scale entrepreneurs in the urban water and sanitation market. Environment and Urbanization. 1999a; 11:117–132.

Solo TM. Small-scale entrepreneurs in the urban water and sanitation market. Water and Sanitation. 1999b; 11

Stokes J, Horvath A. Life cycle energy assessment of alternative water supply systems. International Journal of Life Cycle Assessment. 2005; 11:335–343.

Streicher-Porte M, Widmer R, Jain A, Bader HP, Scheidegger R, Kytzia S. Key drivers of the e-waste recycling system: assessing and modelling e-waste processing in the informal sector in Delhi. Environmental Impact Assessment Review. 2005; 25:472–491.

Vince F, Aoustin E, Breant P, Marchal F. LCA tool for environmental evaluation of potable water production. Desalination. 2008a; 220:37–56.

Vince F, Austin E, Breant P, Marchal F. LCA tool for environmental evaluation of potable water production. Desalination. 2008b; 220:37–56.

Wagah GG, Onyango GM, Kibwage JK. Accessibility of water services in Kisumu Municipality, Kenya. Journal of Geography and Regional Planning. 2010; 3:114–125.

Whittington D, Laura DT, Mu X. A study of water vending and willingness to pay for water in Onitsha, Nigeria. World Development. 1991; 19:179–198.

WHO. UNICEF. WHO. , editor. Progress on Sanitation and Drinking Water. 2012 Update (Geneva). 2012.

World Bank. Water Resources Sector Strategy: Strategic Directions for World Bank Engagement. 2004.

World Resources Institute. Kenyan Census. 1999.

Zuin V, Ortolano L, Alvarinho M, Russel K, Thebo A, Musimpua O, Davis J. Water supply services for Africa's urban poor: the role of resale. Journal of Water and Health. 2011; 9:773–784. [PubMed: 22048436]

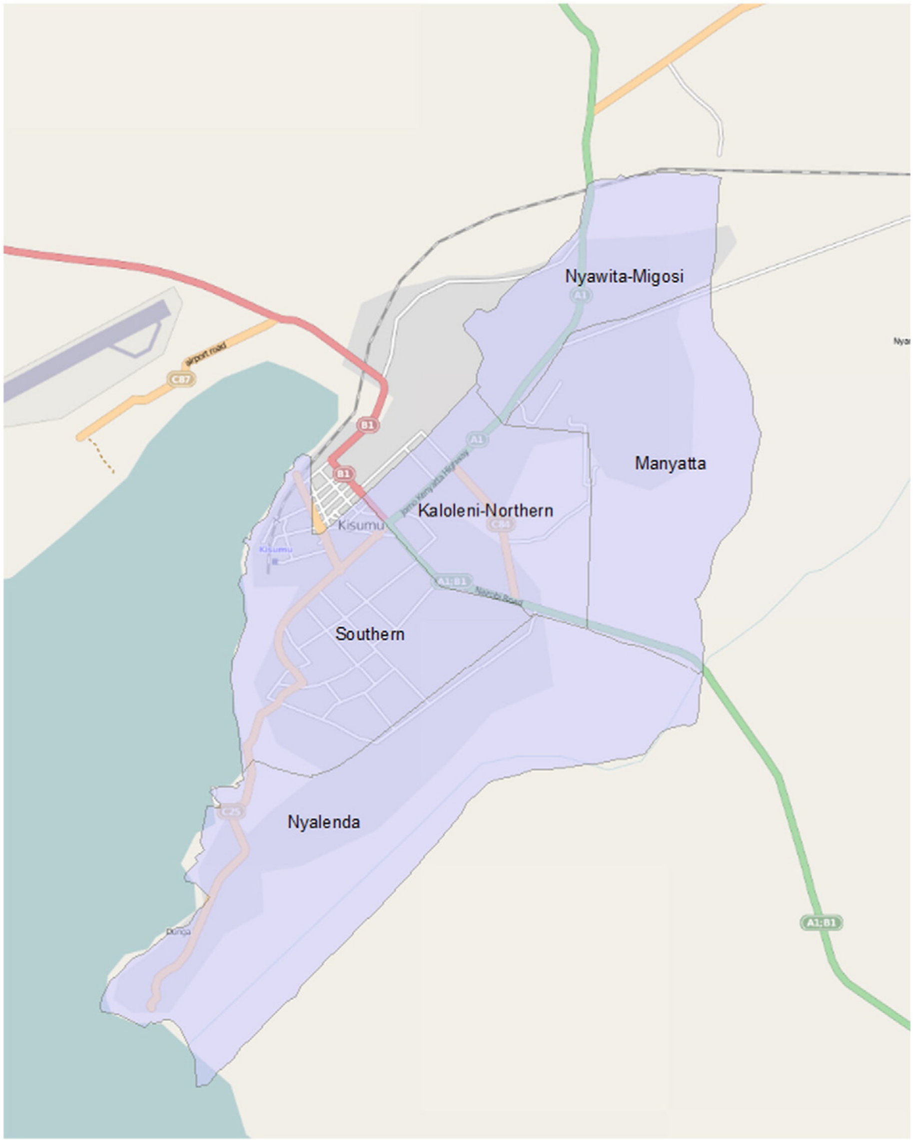

Fig. 1.
Map of Kisumu, including neighborhood boundaries used for data analysis.

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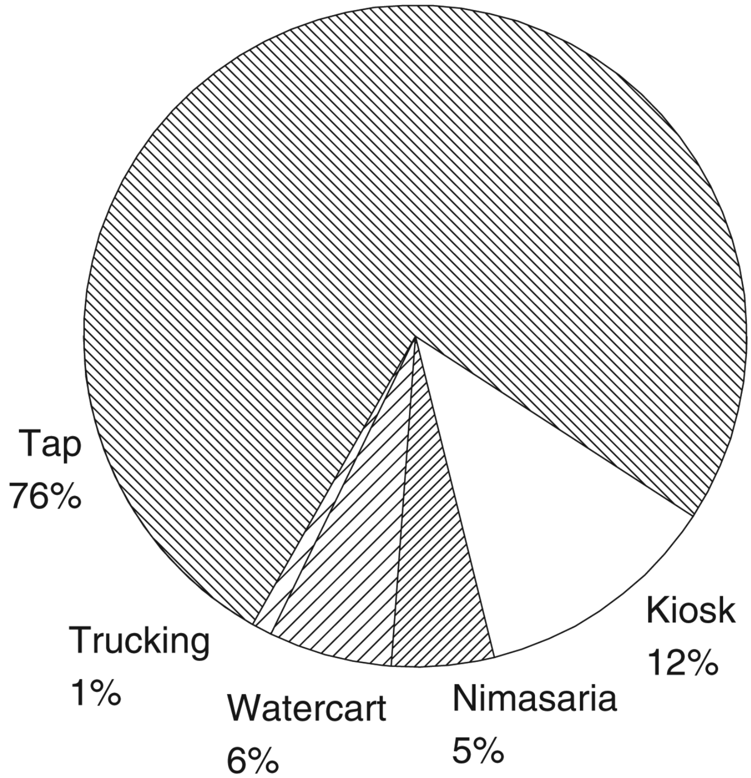

Fig. 2.
The volumetric distribution of water provided to households by water source.

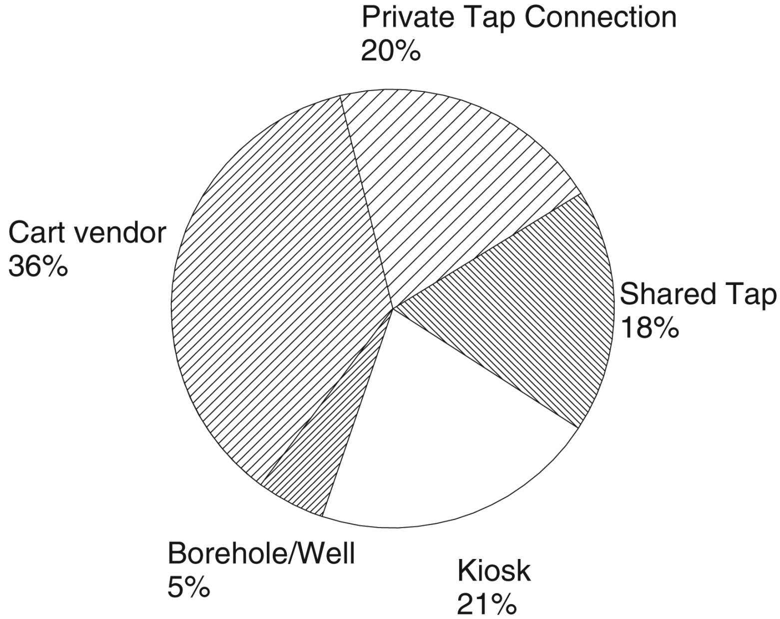

Fig. 3.
The per-household distribution of water provided to households by water source.

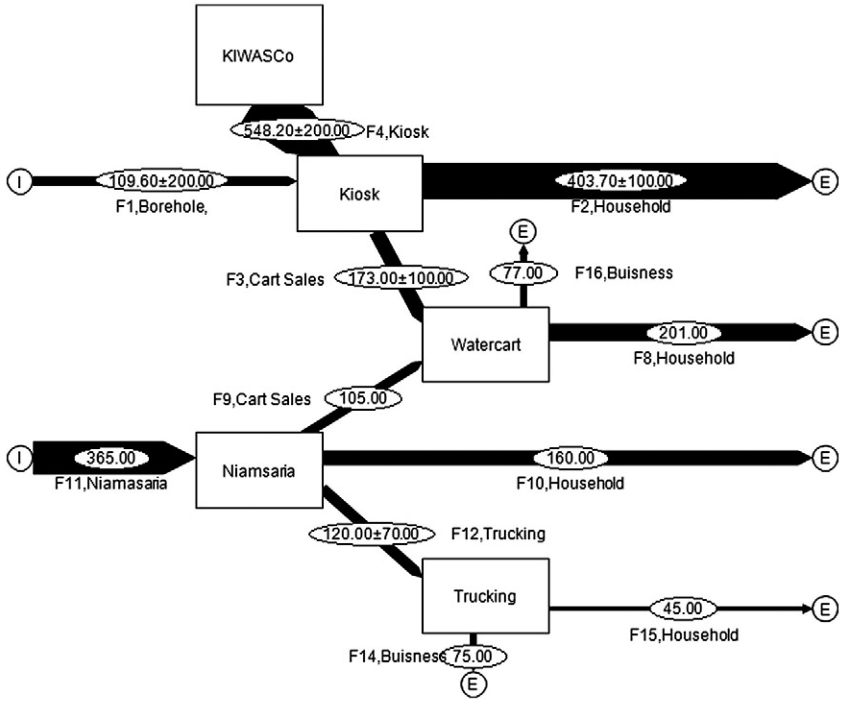

Fig. 4.

Volumetric flow of water in the informal sector. Analysis and image were created with STAN, a free software that supports material flow analysis. All values above are cubic meters/day.

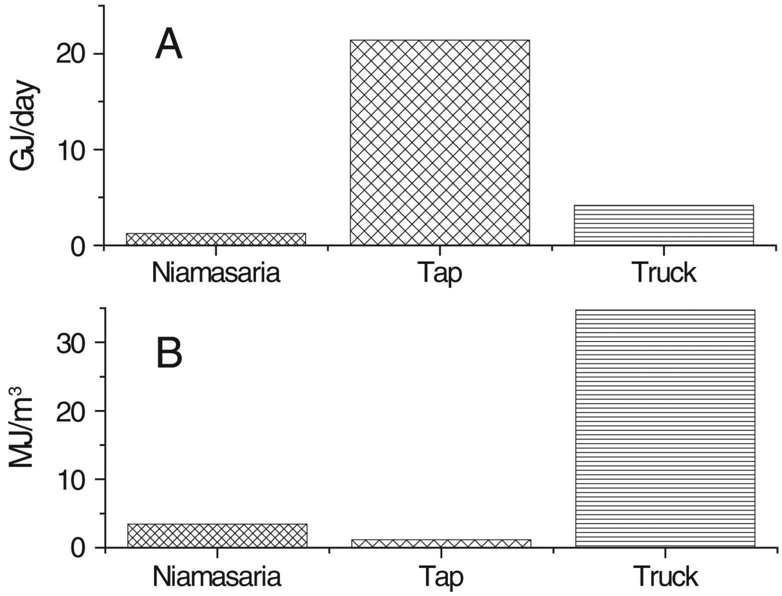

Fig. 5.
Resource use by service type. Total daily resource use by service type (A), and total resource use per household serviced per day (B). Numbers are estimated based on flow volumes presented in Fig. 4, resource use measures and estimates provided by operators of the businesses, and energy estimates for various resources collected from available literature.

Table 1

Description of kiosk characteristics based on survey responses by neighborhood in Kisumu, Kenya.

	Kaloleni-Northern n=47	Manyatta n=15	Nyalenda n = 44	Nyawita-Migosi n=64	Southern n=5	p-Value
Price (KSh/20 L), mean (±stdev)	11.4 (±8.11)	2.82 (±0.75)	2.74 (±0.65)	4.16 (±3.03)	4.8 (±5.72)	< 0.001
Number of jerrycans waiting to be filled, mean (± stdev)	17.3 (±25.15)	24.9 (±53.5)	7.88 (±6.8)	21.2 (±22.1)	6 (±13.42)	0.037
Kiosk is drawing water from municipal system, n (%)	32 (68%)	10 (67%)	39 (89%)	56 (87%)	5 (100%)	0.019
Kiosk is operated by						0.042
a household, n(%)	35 (76%)	8 (53%)	36 (84%)	41 (64%)	5 (100%)	
a small business, n (%)	11 (24%)	7 (47%)	3 (7%)	17 (27%)	0 (0%)	
a women's group, n(%)	2 (4.3%)	0 (0%)	6 (14%)	6 (9.4%)	0 (0%)	

Table 2

Description of demographic information based on census data by neighborhood in Kisumu, Kenya.

	Kaloleni-Northern	Manyatta	Nyalenda	Nyawita-Migosi	Southern
Population density 2009 (residents/km^2)	7198	15,501	7713	10,671	1760
Population growth, 1999–2009 (residents/km^2)	578.95	3641.05	2523.01	1138.34	–319.22
Source of drinking water					
From a borehole spring of well	542 (22%)	24,312 (32%)	3883 (6.4%)	9035 (26%)	92 (1%)
Piped into dwelling	4757 (19%)	1799 (2.4%)	2835 (5%)	3116 (9%)	4304 (47%)
Piped form community location	11,380 (46%)	25,941 (34%)	46,613 (77%)	7342 (21%)	3757 (41%)
Water cart vendor	7963 (32%)	22,586 (30%)	4856 (8%)	14,485 (42%)	1100 (12%)
Source of sanitation					
Connected to main sewer	15,713 (64%)	3199 (4%)	741 (1%)	7696 (22%)	5544 (61%)
Private sanitation with septic tank	984 (4%)	2231 (3%)	2456 (4%)	7366 (21%)	2896 (32%)
Private latrine	911 (4%)	4653 (6%)	3179 (5%)	1441 (4%)	183 (2%)
Uncovered latrine	6869 (28%)	65,109 (86%)	53,179 (88%)	17,753 (51%)	421 (5%)

Table 3

Description of water pricing and line length (proxy for demand) at kiosks supplied by water from the municipality and from boreholes by neighborhood in Kisumu, Kenya.

	Prices (Kenyan shillings/20 L)			Line Length (# of 20 L containers to be filled)		
	Piped water	**Groundwater**	**p-Value**	**Piped water**	**Groundwater**	**p-Value**
Kaloleni-Northern, mean (±std)	9.8 (±6.8)	14 (±10)	0.03	21 (±27)	12 (±21)	0.141
Manyatta, mean (±std)	3.2 (±0.7)	2.15 (±0.3)	0.18	33 (±65)	9.0 (±11)	0.12
Nyalenda, mean (± std)	2.8 (±0.7)	2.5 (±0.6)	0.91	7.3 (±6.2)	12 (±12)	0.06
Nyawita-Migosi, mean (± std)	4.3 (±3.1)	3.1 (±2.5)	0.74	22 (±22)	18 (±21)	0.83
Southern, mean (± std)	4.8 (±5.7)	–	–	6.0 (±13)	–	–