Inequalities in microbial contamination of drinking water supplies in urban areas: the case of Lilongwe, Malawi

Akosua Sarpong Boakye-Ansah, Giuliana Ferrero, Maria Rusca and Pieter van der Zaag

ABSTRACT

Over past decades strategies for improving access to drinking water in cities of the Global South have mainly focused on increasing coverage, while water quality has often been overlooked. This paper focuses on drinking water quality in the centralized water supply network of Lilongwe, the capital of Malawi. It shows how microbial contamination of drinking water is unequally distributed to consumers in low-income (unplanned areas) and higher-income neighbourhoods (planned areas). Microbial contamination and residual disinfectant concentration were measured in 170 water samples collected from in-house taps in high-income areas and from kiosks and water storage facilities in low-income areas between November 2014 and January 2015. Faecal contamination (*Escherichia coli*) was detected in 10% of the 40 samples collected from planned areas, in 59% of the 64 samples collected from kiosks in the unplanned areas and in 75% of the 32 samples of water stored at household level. Differences in water quality in planned and unplanned areas were found to be statistically significant at $p < 0.05$. Finally, the paper shows how the inequalities in microbial contamination of drinking water are produced by decisions both on the development of the water supply infrastructure and on how this is operated and maintained.

Key words | drinking water quality, faecal contamination, low-income urban areas, Malawi, water utility management

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INTRODUCTION

It is well established that inadequate access to safe drinking water and basic sanitation is a major cause of diseases worldwide. Diarrhoeal incidences account for 1.5 million fatalities yearly (WHO 2012), of which approximately 360,000 occur in children under five (WHO 2014). Large-scale programs such as the Drinking Water Decade (1981–1990) and the Millennium Development Goals have placed access to drinking water at the core of the development agenda. These programs, however, seem to focus on coverage, while other fundamental dimensions, including reliability of supply, affordability and quality are overlooked (Bain *et al.* 2014; Shaheed *et al.* 2014a). The Drinking Water Decade (1981–1990) framed lack of adequate water services in the Global South as a 'hardware' problem (Ahlers *et al.* 2013). Similarly, the Millennium Development Goal 7 (Target 10), which sought to halve by 2015 the proportion of the population without sustainable access to safe or improved drinking water, defined improved access as a percentage of coverage. Improved water sources are equated to a set of technologies for transporting and distributing water, such as tube wells, boreholes household connections, and public taps (WHO/UNICEF JMP 2012).

Coverage, we argue, is not a comprehensive indicator of improved access. First of all, research shows that so-called 'improved water sources' do not always ensure access to safe water. In Blantyre, Malawi, for instance, the microbiological

doi: 10.2166/wh.2016.258

quality of water from wells did not meet the WHO guideline values nor the regulations of the Malawi Board of Standards. Faecal contamination was detected in all samples during the wet season and in 80% during the dry one (Pritchard *et al.* 2007). Similarly, a study conducted in different parts of Ghana showed that the chemical water quality (NO_3^-, Mn, F^-, Fe, Pb, and other heavy metals) of 38% of the water samples collected from boreholes, wells and piped water supply systems did not comply with the WHO guidelines (Rossiter *et al.* 2010). Secondly, research shows that the centralized water supply network does not always eliminate risks of water contamination. Two studies on networked water supply conducted in the low-income areas of Accra, Ghana and in 94 peri-urban households in Kandal Province, Cambodia, demonstrated that faecal contamination also occurs in piped water supply (Machdar *et al.* 2013; Shaheed *et al.* 2014b). The aforementioned research, however, does not address the question of distribution of water contamination within the centralized water supply network.

In this paper we undertake a comparative analysis of water quality distributed through the centralized water supply network to low-income unplanned areas (LIAs) and higher-income planned areas (HIAs) in Lilongwe, Malawi. Further, the drivers, often overlooked in drinking water quality assessments, underlying variations of water quality in the system are identified. To do so, this study analyses decisions on the development, operation and management of water supply infrastructure in the city. Further, the role of drinking water quality regulations and its enforcement in producing differentiated water quality in the centralized water supply network is analysed.

METHODS

Study area

This study was carried out in Lilongwe, the capital of Malawi. The city has an estimated population of approximately 1 million inhabitants (UN-HABITAT 2011), subdivided into 58 areas. Of these 26 are classified as LIAs, with a population of approximately 412,000 people (NSO 2008). The Lilongwe Water Board (LWB), established in 1947, is a parastatal body operating on a commercial basis and mandated to supply water in Lilongwe city. Before the capital relocation (1960) the water supply network only covered three areas of the city (Areas 1, 2 and 3). In the 1970s the network was extended to the Parliament buildings, HIAs, industries, banks, hotels and part of the city centre (i.e. Area 20, 12, 15, 27, 35, 13, 16, 19 and 25) (Rusca *et al.* 2015). Currently the LWBs network covers 78% of the city population, while the remaining 22% access water through shallow wells and boreholes (NSO 2008). LWB water is provided through two distinct technologies: 37% of the population is served through in-house connections and 41% through water kiosks (NSO 2008).

Raw water is accessed from two dams (Kamuzu Dam I and Kamuzu Dam II) built along the Lilongwe River. The raw water flows over a distance of 20 km from the dam sites and is treated at two treatment plants with a combined capacity of 95,000 m^3/day (Kosamu *et al.* 2013). Raw water is treated through aeration, coagulation, flocculation, sedimentation and filtration. Chlorine disinfection is carried out before the treated water is transported to the ten reservoirs located in different parts of Lilongwe and at the reservoirs, where further chlorination is carried out once per week.

Sampling

Drinking water samples were collected from two low-income areas (Area 56: LIA_1 and Area 7: LIA_2) and two higher-income areas (Area 47: HIA_1 and Area 2: HIA_2). Whilst the LIAs are served by the Mwenda reservoir, the HIAs are served by Mutunthama and Area 9 reservoirs. Sampling was carried out over a relatively dry period for 3 months, November 2014 to January 2015 (Figure 1).

Given the comparative nature of the study, the main selection criteria for sampling points were the focus on the area supplied by the formal water provider, the technology used to provide water (in-house connections and water kiosks), and the socio-economic characteristics of the areas. In particular, residents in HIA_1 and HIA_2 are served through in-house connections, while LIA_1 and LIA_2 are served through water kiosks (Table 1). Additionally, the selection of sampling points was dictated by the attempt to maximise the variation of water point type as well as achieving a homogeneous spatial distribution, but also ultimately linked to the accessibility of sampling points.

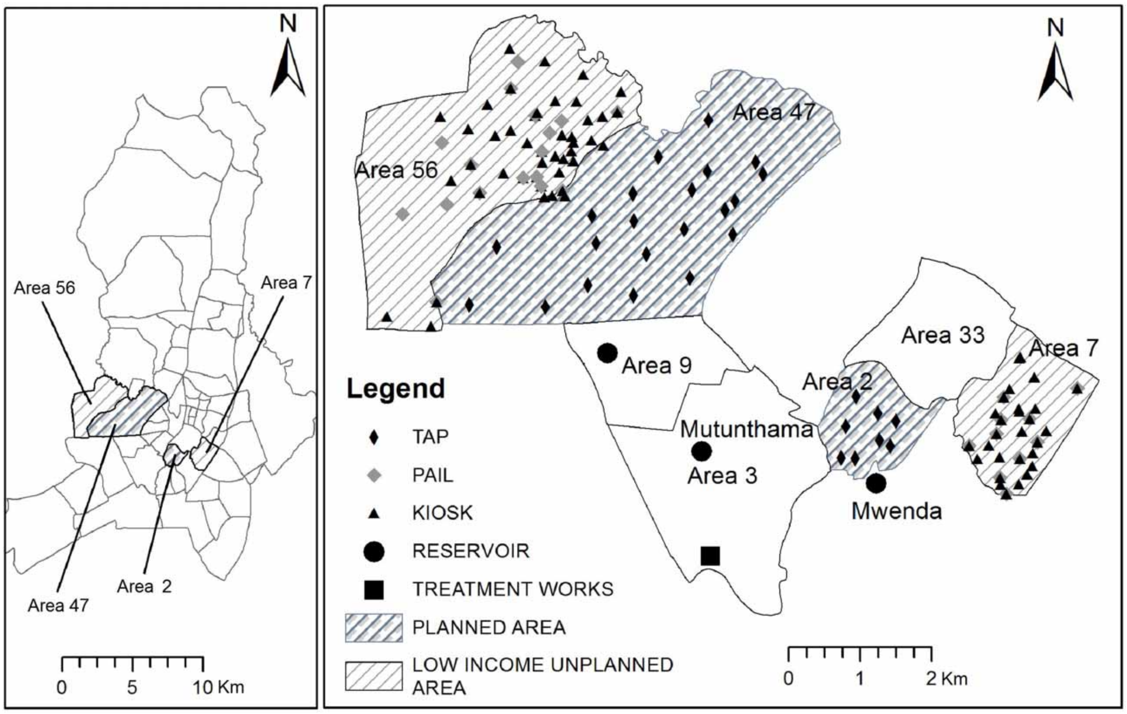

Figure 1 | (a) Map of Lilongwe municipality and the four sampling areas; and (b) detailed map of four areas, distinguishing planned and unplanned areas, with the sampling points.

Table 1 | Number of samples collected

Sampling points		**Population**	**Number of samples**
Water treatment	Outlet treatment works	526,500	19
Reservoirs	Mutunthama	115,800	6
	Area 9	42,000	6
	Mwenda	103,500	6
High income	Area 47 – HIA_1	8,100	30
Planned areas	Area 2 – HIA_2	3,000	10
Low income unplanned areas	Area 56 – LIA_1	36,700	
	Kiosks	–	45
	Household stored water	–	22
	Area 7 – LIA_2	40,000	
	Kiosks	–	19
	Household stored water	–	10
TOTAL			*170*

Sampling procedure

Samples for microbiological analysis (*Escherichia coli* and total coliforms) were collected in sterile 300 mL Pyrex bottles containing 3% sodium thiosulphate to quench residual chlorine. They were stored in an insulated cool box containing ice packs and transported to the laboratory where they were processed within a few hours of collection. Samples from kiosks, reservoirs and in-house connections were collected directly after flaming the tap (where possible) and allowing the water to run for 2–3 minutes. Samples from household stored water in low-income areas were poured directly from the open storage containers used by the residents into the sterile bottles.

Analytical methods

Selected physicochemical and microbiological analyses were carried out according to *Standard Methods* (APHA 2012): Method 2130 B for Turbidity, 4500 Cl G for free and total residual chlorine, 2550 B for temperature, 9222 for *E. coli* and total coliforms. Temperature, turbidity and pH were measured in the field with a thermometer, a turbidity meter (HACH CAMLAB 2100N) and a pH meter (WTW 340i), respectively. Likewise, free and total chlorine were analysed in the field by spectrophotometric method using DPD powder pillows (Hach Lange). *E. coli* and total coliforms were enumerated using the membrane filtration method, where 100 mL samples were filtered on a 0.47 μm membrane filter of 47 mm diameter. The filters were placed on Chromocult agar (Merck) and incubated for 24 hours at a temperature of 37 °C. Dark-blue to violet colonies and salmon to red colonies were counted as *E. coli* and total coliforms, respectively. As a confirmation for the presence of *E. coli*, the dark-blue to violet colonies were coated with KOVAC'S indole reagent (Sigma-Aldrich). A positive indole formation indicated by a cherry-red colour after a few seconds confirmed the presence of *E. coli*. Samples were plated in triplicates.

Qualitative data collection methods: interviews and observations

A total of 71 semi-structured interviews with 67 key stakeholders, including consumers, Water User Associations, private operators, LWB staff, government official and non-governmental organizations, were conducted during this period. In addition to this, observations were made in the field to identify the factors contributing to the changes in the water quality in the distribution system. These included the procedures for breaks and leakages, decisions on depth of pipes, water storage practices, and sanitary conditions of the areas where pipes are laid, as well as the general handling and storage practices.

Quantitative and qualitative data analysis

Data obtained from the analyses of the different water samples were subjected to statistical analysis in order to compare the drinking water quality in the different areas and with respect to the quality of the water supplied by the treatment plant. The non-parametric Kruskal–Wallis H test was used to determine if the differences between the averages for the different tests including the triplicates for the microbiological tests were statistically significant at 95% confidence interval ($p < 0.05$). For the purpose of statistics, colonies for total coliforms and *E. coli* which were too numerous to count were represented by 10^4 CFU/100 mL. Additionally, data were compared to WHO guideline values (WHO 2011) and the standards adopted by the LWB. As for the qualitative analysis, data were codified in four main categories: decisions on development and design of the water network; operation and maintenance of the system; water quality regulations and monitoring; and storage practices. Analysis focused on the relation between these categories and water quality at sampling points.

RESULTS

Water quality assessment

The analysis of microbiological parameters (*E. coli* and total coliforms) and physico-chemical parameters (turbidity and residual chlorine) clearly showed the variation in water quality from the treatment plant to the tap (both in-house connections and kiosks).

The concentration of *E. coli* and total coliforms was low at the outlet treatment works and reservoirs, but increased as the water flowed to the settlements (Figure 2, Table 2). *E. coli* and total coliforms concentrations, however, were higher at the kiosks, and, even more, in the water stored at household level. *E. coli* and total coliforms were detected in 64% and 98%, respectively, of the samples collected from kiosk samples in LIA_1. Whereas in LIA_2, 47% and 74% of the 19 samples collected from kiosks contained *E. coli* and total coliforms.

As for the water stored at household level, *E. coli* was detected in 91% of samples from LIA_1 and all samples in LIA_2, while total coliforms were detected in all of the samples. In higher income areas, microbial contamination was lower than in the low-income areas, but nevertheless, 57% ($n = 30$) of the samples collected in HIA_1 showed the presence of total coliforms and 3% showed the presence of *E. coli*. Similarly, in HIA_2, total coliforms and *E. coli* were detected in 70% ($n = 10$) and 30% ($n = 30$), respectively, of the samples collected.

The differences detected in the microbial contamination between the outlet treatment works and the reservoirs were not statistically significant for *E. coli* ($H(3, N = 37) = 1.19$, $p < 0.05$) or total coliforms ($H(3, N = 37) = 0.66$, $p < 0.05$). Likewise the differences between the mean *E. coli*

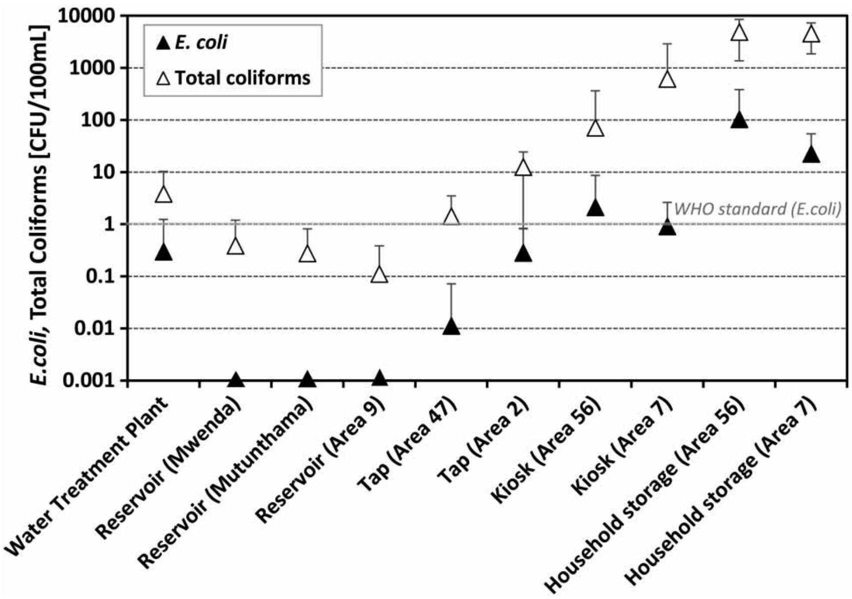

Figure 2 | Mean *E. coli* and total coliforms concentrations detected in different water sources in Lilongwe.

contamination, detected in samples from the higher income areas (HIA$_1$ and HIA$_2$) and the outlet treatment works were not significant ($H(2, N = 59) = 5.07$, $p < 0.05$). However, a larger sample size may present different results. For total coliforms, whilst the numbers detected in HIA$_1$ ($M = 1.7$ CFU/100 mL, $SD = 2.1$) were lower than that from the treatment works, numbers detected in HIA$_2$ ($M = 12.6$ CFU/100 mL, $SD = 11.8$) were higher. These differences were also statistically significant ($H(2, N = 59) = 8.97$, $p < 0.05$). The situation was different in the low-income areas: the mean *E. coli* and total coliforms detected in all samples for both kiosk and household-stored water were higher than the counts at the outlet treatment works, reservoirs and planned areas, which suggest a contamination before or at the kiosks and at household level. The differences observed in the mean values of microbial contamination at the LIAs (kiosks and households) and at the outlet treatment works was statistically significant (*E. coli* in kiosks: $H(2, N = 83) = 7.60$, $p < 0.05$ and in households: $H(2, N = 51) = 16.97$, $p < 0.05$ and total coliforms in kiosks: $H(2, N = 83) = 31.37$, $p < 0.05$ and in households: $H(2, N = 51) = 35.08$, $p < 0.05$). A similar result was obtained by statistically comparing the means of microbial indicators in HIAs and in LIAs, both for kiosks and households (*E. coli* in kiosks: $H(3, N = 104) = 21.44$, $p < 0.05$ and in households: $H(3, N = 72) = 29.77$, $p < 0.05$ and total coliforms in kiosks: $H(3, N = 104) = 47.37$, $p < 0.05$ and in households: $H(3, N = 72) = 55.04$, $p < 0.05$). Also differences observed between the means of samples collected from kiosks and household-stored water were significant for both *E. coli* ($H(3, N = 96) = 19.52$, $p < 0.05$) and total coliforms ($H(3, N = 96) = 65.70$, $p < 0.05$). This indicates that the differences in the mean values are not a result of chance and are significant.

In terms of residual disinfectant concentration, the mean value of total chlorine ranged from a minimum of 0.1 mg/L ($SD = 0.04$) for household-stored water in LIA$_2$ to a maximum of 2.6 mg/L ($SD = 1.3$) at the outlet treatment works (Figure 3). As water is transported from the treatment works through the reservoirs to the different areas, free and total chlorine concentration reduced. The reduction in the mean concentration of residual chlorine from the outlet treatment works to the reservoirs was significant (free chlorine $H(3, N = 37) = 13.19$, $p < 0.05$ and total chlorine $H(3, N = 37) = 8.85$, $p < 0.05$). This reduction was also significant from the treatment works up to the points of consumption in the HIAs (free chlorine $H(2, N = 59) = 34.14$, $p < 0.05$ and total chlorine $H(2, N = 59) = 33.06$, $p < 0.05$) as well as in the LIAs for both kiosks (free chlorine $H(2, N = 83) = 43.31$, $p < 0.05$ and total chlorine $H(2, N = 83) = 43.33$, $p < 0.05$), and at household level (free chlorine $H(2, N = 51) = 35.09$, $p < 0.05$ and total chlorine H

Table 2 | Water quality data (M: mean; Mdn: median; SD: standard deviation)

	pH			**Temperature (°C)**			**Turbidity (NTU)**			**Free chlorine (mg/L)**			**Total chlorine (mg/L)**			***E. coli*** **(CFU/100 mL)**			**Total coliforms (CFU/100 mL)**		
Sampling points	**M**	**Mdn**	**SD**	**M**	**Mdn**	**SD**	**M**	**Mdn**	**SD**	**M**	**Mdn**	**SD**	**M**	**Mdn**	**SD**	**M**	**Mdn**	**SD**	**M**	**Mdn**	**SD**
Treatment works	7.8	7.7	0.3	25.8	25.8	1.6	0.9	0.9	0.6	2.1	2.0	1.0	2.6	2.1	1.3	0.3	0.0	0.9	3.8	0.0	6.4
Reservoirs																					
Mwenda	7.7	7.7	0.3	26.1	25.9	1.2	1.1	1.2	0.3	1.1	1.2	0.3	1.8	2.0	0.5	0.0	0.0	0.0	0.4	0.0	0.8
Muthuntama	7.3	7.3	0.1	26.6	27.1	1.3	1.1	1.2	0.1	1.4	1.5	0.6	1.6	1.6	0.7	0.0	0.0	0.0	0.3	0.0	0.5
Area 9	7.5	7.5	0.1	26.7	26.7	0.4	1.0	1.0	0.1	1.1	1.1	0.3	1.2	1.3	0.2	0.0	0.0	0.0	0.1	0.0	0.3
Planned areas																					
Area 47 –HIA_1	7.5	7.5	0.1	27.9	28.0	1.1	1.2	1.1	0.6	0.7	0.7	0.2	0.9	0.9	0.3	0.0	0.0	0.0	1.7	0.9	2.1
Area 2 – HIA_2	7.8	7.8	0.1	27.0	27.0	0.9	1.6	1.5	0.6	0.7	0.7	0.2	0.9	0.8	0.2	0.3	0.0	0.5	12.6	10.4	11.8
Low-income areas																					
Area 56 – LIA_1 kiosks	7.6	7.6	0.2	26.2	26.2	1.8	2.9	1.7	3.8	0.5	0.4	0.3	0.6	0.5	0.3	2.1	0.3	6.6	71.5	5.3	289.4
Area 7- LIA_2 kiosks	7.8	7.8	0.2	26.2	26.3	0.6	7.2	4.1	12.0	0.4	0.5	0.2	0.5	0.6	0.2	0.0	0.0	1.7	614.4	46.7	2,278.0
Area 56 – LIA_1 households	7.6	7.6	0.2	26.2	26.5	1.8	2.8	2.9	1.8	0.1	0.0	0.1	0.1	0.1	0.1	103.4	6.2	280.1	4,907.9	5,153.3	3,543.5
Area7 – LIA_2 households	7.8	7.8	0.2	26.1	26.6	0.9	3.1	2.9	1.8	0.0	0.0	0.0	0.1	0.1	0.0	22.4	2.8	31.8	4,584.4	5,287.5	2,715.3

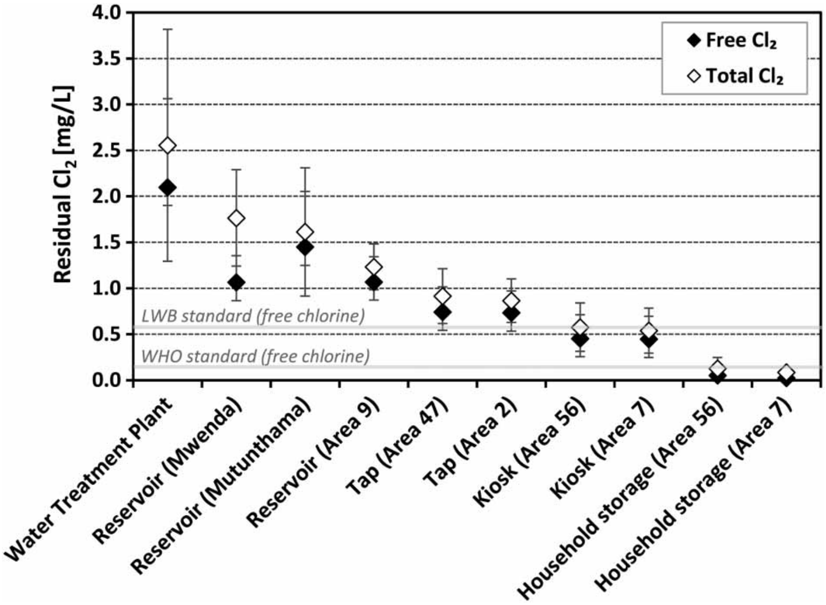

Figure 3 | Mean free and total residual chlorine measured in the different water sources in Lilongwe.

$(2, N = 51) = 35.11, p < 0.05$). Further, a significant difference was observed in the reduction of both free chlorine ($H = 51.89$, $p < 0.05$) and total chlorine ($H(3, N = 96) = 52.10$, $p < 0.05$) from the kiosks to the points of consumption (household level). With the exception of samples from the outlet of the treatment works and reservoirs conforming to WHO and LWB standards, only part of the samples collected from the various areas complied with these standards. In the planned areas, all samples collected in HIA_2 showed free chlorine values complying with the WHO guideline of 0.2 mg/L, whilst 3% of samples from HIA_1 were incompliant; however, when comparing with the more restrictive LWB standard of 0.5 mg/L, 47% and 40% of the samples analysed for LIA_1 and LIA_2 did not comply. In the LIAs, 100% of the samples of water stored at household level in LIA_2 presented free chlorine concentrations below both WHO guidelines and LWB standard; similarly, 91% of samples from LIA_1 did not comply with the WHO guideline value.

Drinking water turbidity is commonly used as a proxy measure for microbial contamination of water supplies; the mean turbidity values recorded ranged from a minimum 0.9 NTU ($SD = 0.6$) for the outlet treatment works to a maximum of 7.2 NTU ($SD = 12.0$) for samples collected from kiosks in HIA_2 (Table 2). With the exception of the samples from the outlet treatment works, turbidity recorded at all sampling points was above the WHO guideline value of 1.0 NTU. For the planned areas 63% of samples collected in HIA_1 and 80% of the samples collected in HIA_2 recorded turbidity levels that did not comply with the WHO guideline value. Whilst in the LIAs, 82% and 90% of samples collected from kiosks in LIA_1 and LIA_2 respectively, and 90% of the water stored in households in LIA_2 and 82% from LIA_1 did not comply with the WHO guideline value. However, with the standards established by LBW being less restrictive than WHO guideline, only in 7% and 16% of samples from kiosks in LIA_1 and LIA_2, and in 9% and 10% of samples from their corresponding water stored at household level, turbidity exceeded the value of 5.0 NTU stipulated by LWB. Although the turbidity recorded at the outlet treatment works was higher than that recorded at the reservoirs, these differences were not significant ($H(3, N = 37) = 3.01$, $p < 0.05$); the increase in turbidity was however significant for samples from HIAs ($H(2, N = 59) = 7.51$, $p < 0.05$) as well as in the LIAs for both kiosks ($H(2, N = 83) = 37.03$, $p < 0.05$) and households ($H(2, N = 51) = 18.71$, $p < 0.05$). Also lower mean turbidity values were recorded for samples of water stored at household level (Table 2) in comparison with water samples from kiosks. These differences were significant ($H(3, N = 96) = 20.75$, $p < 0.05$) for samples from both LIAs.

The pH measured in water samples ranged from a mean minimum of 7.3 ($SD = 0.1$) at Mutunthama reservoir to a maximum of 7.8 ($SD = 0.3$) at the treatment plant. pH values measured in all sampling points were in line with WHO guideline value of 6.5–8.5. Temperature ranged from a minimum of 25.8 °C ($SD = 1.6$) for water from the treatment works to a maximum of 27.8 °C ($SD = 1.1$) for water samples collected from HIA_1.

Managing water quality: development, operation and maintenance of the supply network

The LWB has adopted different strategies for network development in high-income and low-income areas. For instance, the LWB has opted for larger and better quality pipes in the planned high-income areas which are, paradoxically, less populated. The densely populated low-income areas are supplied with a rather scattered network, composed of a lower number of smaller pipes of lesser quality (Figure 4).

The result of this is 106,000 m^3/month of water delivered to HIA_1, 69,000 m^3/month to HIA_2, 43,600 m^3/month to LIA_2 and 17,900 m^3/month to LIA_1.

Whilst 90% of households in the planned areas are connected with high quality HDPE pipes, kiosks in LIAs are connected with galvanized iron pipes, which are susceptible to corrosion. In addition, everyday operation of the network determines a situation in which high-income areas enjoy semi-continuous supply, while low-income areas experience highly intermittent supply (Vidal *et al.* 2016). Discontinuity of supply contributes to the aforementioned differences in volume. Further, LWB recommends a depth of 100 cm from the top of the pipe to the ground surface for the pipes connecting the reservoirs to the areas (transmission pipes) and 45 to 50 cm (from the trench to the surface) for the pipes connecting the various households and kiosks (connecting pipes).

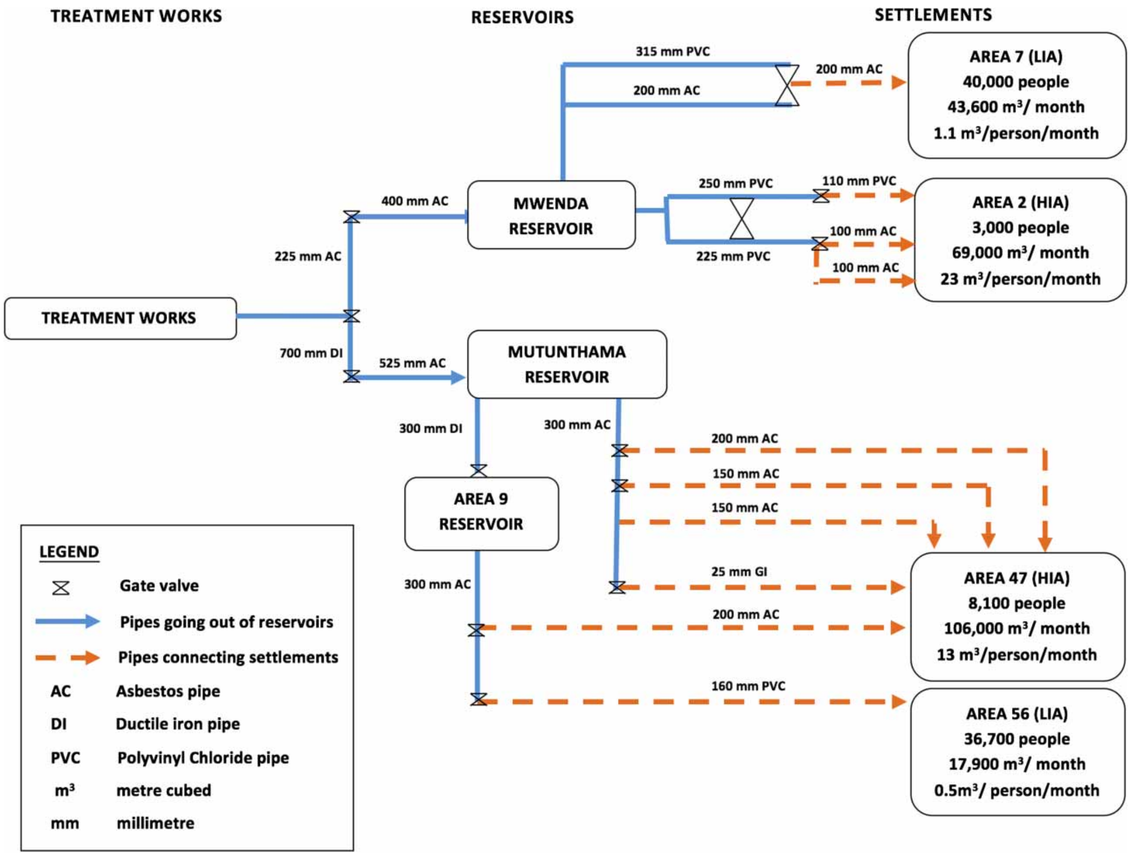

Figure 4 | Transmission network of the study area.

The implementation of this recommendation, however, varies from area to area: while in planned areas pipe networks are lowered enough to prevent them from being easily exposed and susceptible to breakages and leakages, this is not done in low-income areas, where pipes are scattered on roads and walkways. This is a result of the lack of supervision of contractors by the LWB during the works for laying pipes in these areas, in contrast to what happens in planned areas.

In addition to this, utility managers deal with the limited water available by prioritizing higher income areas at the detriment of lower income neighbourhoods. Being a parastatal commercial entity, the LWB prefers to connect a higher number of larger pipes to planned areas where cost recovery is assured and revenue generation is high. As a result the network is operated in such a way that supply to planned areas is continuous with high pressure (minimum flow of 13.3 L/min; maximum flow of 24 L/min) whilst LIAs experience intermittent flows with regular cut-offs and low pressure (minimum flow of 2.5 L/m and maximum flow of 7.6 L/min).

Maintenance practices of the LWB result in another form of prioritization, which further deteriorates the quality of water supplied to the low-income areas. While it takes a maximum of three days for maintenance activities to be carried out in the HIAs, it takes up to 3 months or more in the LIAs. The accumulated effect of low pressure, cut-offs and scarce maintenance is therefore translated into ingress of soil and faecal matter into the distribution pipes, leading to the deterioration of water quality mainly in low-income areas.

Regulation of water quality

Water quality standards (MS 214: 2013 and MS 678: 2013) were developed by the Malawi Bureau of Standards (MBS) by setting up committees of different stakeholders including the city councils, consumer associations, educational institutions, industries, water utility companies and health directorates. The standards regulate both operational and surveillance monitoring mechanisms. However, according to the body in charge of water supply in Malawi, Ministry of Irrigation Agriculture and Water Development (MoIAWD), these standards apply to rural water supply systems, where the conventional water treatment process of coagulation, sedimentation, filtration and disinfection is not in place. For urban water supply, where the conventional water treatment process is applied, the WHO guidelines for drinking water are used together with the LWB standards.

Water quality in Lilongwe is routinely monitored by the water quality department of the LWB. In theory, the Water Quality Division of the MoIAWD is the entity responsible for the independent surveillance of water supply in the city. However, in practice there is no independent surveillance and enforcement of water quality standards. Therefore, the only form of water quality monitoring in Lilongwe is carried out by the LWB itself. The Act (Waterworks Act 1995) that establishes the water boards is also silent on water quality issues. Moreover, the LWB appears to concentrate the monitoring activities on the planned areas, which are monitored more frequently. Whilst the number of samples collected in low-income areas was lower than the minimum number per the population size recommended by WHO (i.e. for 5,000 to 100,000 inhabitants, 12 samples per 5,000 inhabitants), the number of samples collected in planned areas was above the minimum (Table 3).

Drinking water handling and storage practices

The characteristics of the water supply network and its operation also influence consumers' practices to access water which ends up contributing to further changes in the drinking water quality. In the low-income areas consumers access water through kiosks and have to cope with an intermittent supply. The intermittent supply of water by the LWB coupled with the walking distances to kiosks prompt consumers to store water for use during cut-offs and also to save the time spent fetching the water. In the LIAs residents walk with uncovered pails to kiosks and they usually wait for their turn in long queues. Pails were not washed before being filled, because residents cannot afford to pay an extra amount to have them cleaned at the kiosks. Filled pails are

Table 3 | Number of samples collected from the planned areas and the LIAs (source LWB)

Area	Population (people)	Number of samples (May–December 2014)	WHO recommended minimum per year
Planned	11,100	85	26
Low-income	76,700	40	184

carried uncovered to houses where they are, once more, stored uncovered. These practices explain the difference microbial contamination ($p < 0.05$ for both *E. coli* and total coliforms) at the kiosks and the household. At household level *E. coli* were present in 82% and 60% of water stored at household level in LIA_1 and LIA_2, respectively.

DISCUSSION

Microbial contamination of water supplies represents a major risk for human health, since it can be a vector for the transmission of pathogenic diseases, particularly deriving from faecal contamination. Just at the beginning of 2015, *E. coli* and faecal matter in drinking water sources in Kampala, Uganda, were identified as the cause of an outbreak of typhoid fever (WHO 2015). In this study *E. coli* was found to be present in all points of access. The degree of contamination, however, was lower at the taps in planned areas and incrementally higher at the kiosks and at households in low-income areas, where water is stored. Low concentrations of faecal contamination, and associated low risk in planned areas in Lilongwe, were also reported by Kosamu *et al.* (2013) who undertook their research in Area 25. When comparing water quality data of Lilongwe with the classification developed by WHO (1997) of health risk based on *E. coli* concentration in drinking water, 38% of samples of water stored at household level in the low-income areas presented an intermediate health risk for consumers and 6% implied high to very high risk. Whilst 56% and 3% of samples from kiosks presented low and intermediate risk, respectively, the risk associated with the samples from the planned areas is, however, low with 10% of samples implying low risk and 90% conforming to the standard.

Nevertheless, the classification of health risk, as well as the indicator commonly used for detecting faecal contamination, comes with limitations. For instance, in piped water supplies that rely on chlorine-based residual disinfectant, there is no guarantee that absence of *E. coli* in taps will be associated with absence of chlorine-resistant pathogens (i.e. *Giardia lamblia*, *Cryptosporidium parvum*) as has been reported in many studies (Korich *et al.* 1990; Venczel *et al.* 1997; Betancourt & Rose 2004; Castro-Hermida *et al.* 2008).

Another finding from this study is that even though residual disinfectant at the point of access (taps and kiosks) complies with the 0.2 mg Cl_2/L recommended by WHO, faecal contamination cannot be prevented. Similar findings have also been reported in Cuba, where faecal coliforms were present in water samples with residual chlorine $\geq$0.3 mg Cl_2/L (Aguiar *et al.* 2000) and in northern Karnataka, India, where *E. coli* was detected in water samples with $>$0.5 mg Cl_2/L (Kumpel & Nelson 2013). Additionally, higher concentrations of *E. coli* were found to be associated with higher levels of turbidity and it is evident in the difference between taps in HIAs and kiosks in LIAs. The differences measured in turbidity provide an indication of the ingress of contaminants through broken pipes in the distribution system, which compromise the quality of the water in transport. The presence of particles in water tends to provide a shield for microorganisms that may be present and may escape the disinfection process (Lynch *et al.* 2014); significant correlation between turbidity and microorganisms has been reported in some studies (LeChevallier *et al.* 1996; Farooq *et al.* 2008).

There is a clear difference in terms of development and design, operation and maintenance of the supply network between HIAs and LIAs. These differences determine the higher contamination detected in unplanned areas. The inequality in water quality that emerged from this study is therefore produced by socio-political decisions concerning the design and management of the supply network by the competent actors and institutions. Specifically, in terms of water infrastructures, two main differences are visible: network density, and selection and positioning of construction materials. Whilst there is a greater number of larger and of better quality pipes connecting the less populated planned HIAs, the densely populated LIAs are connected with a lower number of pipes which are smaller in size and of lower quality. In contrast to the HIAs where pipes are well buried in the ground, pipes are exposed in the LIAs. The presence (or absence) and the working conditions of the valves also determine which of the pipes are more likely to break or can be flushed to eliminate sediments and other foreign materials. Another set of decisions deals with water flows and, more specifically, continuity of the water service. As reported by Kumpel & Nelson (2013), continuous water supply provides water at the taps that have lower concentrations of indicator bacteria than intermittent water supply. Also in this case, decisions taken by the LWB management resulted in the prioritization of the HIAs over the low-income areas, since the continuity of water flows in different parts of the city is not determined by the demand but by the presence of infrastructure and by decisions on operation of the latter. As far as maintenance is concerned, the delayed response in LIAs results in water contamination due to ingress through broken and leaking pipes and also from the resulting intermittent supply and low pressure. These risks of contamination are further increased by unhygienic conditions of the unplanned areas.

Lack of enforcement of drinking water quality regulations worsens the impact of the identified factors on inequalities in the quality of water delivered to consumers. Water quality monitoring is more intense in higher income areas than in LIAs. LWB management attributes the low frequency of monitoring in LIAs to the challenge of collecting samples with frequent cut offs and intermittent supply. Thus, the inequality in infrastructural development, operation and maintenance contributes to producing inequality in monitoring. Further, the omission of quality issues from the Water Boards Act raises questions on the effectiveness of the current monitoring process. The WHO guidelines, generally used by the LWB, set recommended limits that are not mandatory. Therefore in the absence of a legal backing to make them mandatory, it will be difficult for any enforcement actions to be taken in the event standards are not met.

Effective drinking water quality monitoring comprises of both operational and surveillance monitoring, adequate legislation, standards and codes. As a consequence of the incomplete legislations, absence of an independent regulator, lack of coordination between the different entities and inadequate funds, surveillance is absent (Kayser *et al.* 2015). In the absence of surveillance it is difficult to enforce the existing regulations. The lack of enforcement of standards and codes in Lilongwe implies that no one checks the activities of the LWB leaving them in charge of monitoring their own work, at the detriment of LIAs. The limited monitoring activities carried out in low-income areas imply little knowledge of water quality and, in turn, hinder the development of measures to improve the quality of water supplied to these areas.

Last, intermittent supply and distance from the point of access in low-income areas have been reported in many studies to prompt handling and storage practices which further deepens differences in the water quality between the neighbourhoods (Checkley *et al.* 2004; Kumpel & Nelson 2013; Shaheed *et al.* 2014b). Findings from this study are consistent with similar studies on microbial contamination observed in household storage water samples (Yeager *et al.* 1991; Jonnalagadda & Bhat 1995; Jensen *et al.* 2002; Brick *et al.* 2004; Oswald *et al.* 2007; Levy *et al.* 2008; Aish 2013; Kumpel & Nelson 2013; Shaheed *et al.* 2014b). This confirms the high risk associated with water storage and handling practices in peri-urban areas in developing countries.

These findings question the assumption that drinking water from ‘improved’ sources implies water safety, as well as the idea that a centralized networked supply system ensures equal water quality. On the contrary, the study shows that centralized water supply systems are ‘internally fragmented’. Fragmentation is visible in the different materials selected to develop the network and in the uneven water flows in the city. This fragmentation, resulting from decisions of policy makers and utility managers, produces the inequalities in microbial contamination of drinking water supplies in Lilongwe.

CONCLUSION

This study highlighted that drinking water quality deteriorates from the point of treatment to the points of consumption in the different neighbourhoods of Lilongwe. Hence, the perception that treated piped water is an ‘improved’ source and of good quality has proven once again not to be realistic. The water quality deterioration was greater in kiosks in LIAs than in in-house connections in HIAs, where the quality was generally in line with adopted standards. The water quality further deteriorates as it is stored for later use in the LIAs; thus, discontinuity of the service leads to handling and storage practices that further impact the quality of water at the point of use.

The study established that deterioration of water quality during transport and distribution may result in differentiated water quality within the same water supply network. Inequalities in water quality in the water supply network of the formal water utility are attributable to decisions and practices of water service provision. In particular, differentiated water quality is a product of the way in which infrastructure is developed, maintained and operated. In this light, access to 'improved' water sources becomes not only a technical issue but also a political one, and decisions on how and where to develop the network and how to operate it will affect water quality. Understanding inequalities in drinking water quality, therefore, requires an interdisciplinary approach. The interdisciplinary approach adopted in this study enabled the analysis of the socio-political processes influencing the changes and allows for a better understanding of the production of the quality of drinking water in transport.

Finally, it appears clearer that such inequalities can be reduced only by mobilizing resources to improve development, operation and maintenance of water transport and distribution to LIAs, by establishing a sound water quality monitoring programme and by clearly re-defining accountability in water services provision.

ACKNOWLEDGEMENTS

This study was carried out in the framework of research project 'Uncovering Hidden Dynamics in Slum Environments' (UNHIDE) sponsored by the Netherlands Ministry of Development Cooperation (DGIS) through the UNESCO-IHE Partnership Research Fund. The authors acknowledge the participation of the staff and management of Lilongwe Water Board and are grateful for their assistance during the fieldwork.

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First received 18 September 2015; accepted in revised form 13 March 2016. Available online 7 April 2016