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The relationship between water pressure variations and drinking-water quality in small water supplies: A case of Mukono District, Uganda

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ABSTRACT

The supply of a safe and adequate quantity of water is essential for human health and socioeconomic development. Physiochemical and microbiological quality of water supplied in piped distribution systems can be affected by long water residence times and travel distances. This may be due to low pressure, reservoir storage and insufficient disinfection in the system among other causes. As such, large schemes usually have mechanisms of improving the quality of water along supply and/or distribution networks at reservoir and other points. In contrast, small, piped water supply schemes rarely have the infrastructure and resources to monitor and provide treatment to the water in distribution. The objective of this study was to assess the variation of water quality and water pressure along the supply network in small, piped water systems. The study used mixed methods of quantitative water quality and pressure assessments, alongside stakeholder interviews, to investigate the variability of water pressure and specific water quality parameters across the distribution network, and reliability of supply in two different small water supply schemes in the study area of Mukono, Uganda. Results showed water pressure in small, piped water supply networks have minimal influence on variation of selected water quality parameters in smaller ($<$ 4000 m travel distances) and well operated and maintained systems. A pressure drop from 82.2 m to 22.5 m changed Turbidity by < 1, Apparent Color by $<$ x10 and Total Dissolved Solids by $<$ x10^2. Proper management of supply systems to ensure optimal residual and continuous pressure can safeguard the quality of water in the distribution systems of small piped water networks against intrusion of contaminants. Good management practice that utilizes historical operational data with continuous capacity development and training support on water quality and pressure fluctuations can significantly improve system performance to meet acceptable standards.

1. Introduction

Supply of safe and adequate quantity of water is essential for human development both for supporting life and major human activities in society. Communities require consistent access to an adequate quality water which must be acceptable to the community (Chenoweth, 2008). Sustainable development goal target 6.1 calls for universal and equitable access to safe and affordable drinking water (UN, 2015). Water resources are unevenly distributed in many regions in the world, including Africa (Desta et al., 2022; Kebede et al., 2023), increasing the need for water transportation methods from the source to point of consumption. Piped water systems offer a solution to distributing water to meet consumer demand whilst ensuring good quality (Kulinkina et al., 2016; Winter et al., 2021). Households should have indoor access to safe and reliable water to benefit from an improved water supply (Shrestha et al., 2017). Despite increased water coverage in many developing countries, water collection times remain high: a quarter of the population in East Africa travels not less than one hour to fetch water (Geere and Cortobius, 2017). In Uganda, 57 % of the urban population is reported to have access to safely managed water services located on the premises (MWE,

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2020).

In large, often urban, water supply systems, piped water supplies travel long distances and cover a large population and consumer base. Although piped water is often perceived to be potable (WHO and UNICEF, 2017) water consistency and quality can be compromised by network pressure changes (Mustonen et al., 2008), variations in demand or illegal connections (Jacobs and Strijdom, 2009), and long residence times (Hossein et al., 2013a; Desta et al., 2022; Kebede et al., 2023). Changes or insufficiency of system pressure can impose wear on fittings and valves and increase the risk of leaks and bursts (Walski et al., 2003) which can cause intrusion of contaminated water into the water system (Glennon, 2004; Hossein et al., 2013b). Unstable pressures and velocities have been associated with increased turbidity and corrosion in the distribution systems, a factor which affects water quality in the network (Hossein et al., 2013b; Kebede et al., 2023). Long residence times can cause a loss of residual chlorine concentrations and increase the risk of recontamination (Marco et al., 2021). High retention times can reduce the ability to control corrosion effectively by affecting pH management and phosphate inhibitors (NRC, 2007).

Chlorine is used widely in disinfection of drinking water to kill possible harmful organisms which may affect public health. Residual chlorine in the amount of 0.2 mg/l – 0.5 mg/l is the allowable range for safe quality water at the draw off point (El-Dakar, 2016). Residual chlorine reduces with increasing age of water and can even be lost completely, higher substance concentration may leach from pipe materials and lining when the water contact increases (Lee, 2008). Such situations are not acceptable and could lead to customer dissatisfaction and complaints, abandonment of supply systems and reverting to unsafe water sources which ultimately exposes the population to water related diseases. It is therefore important to reduce retention time of water in a supply system by improving the water pressure to achieve safe quality of water distributed. Total coliforms are used as indicator microorganisms for presence of pathogens in drinking water. Water which is safe for consumption should contain zero total coliforms (WHO, 2017).

Half the world's population currently rely on small water supplies with calls made for their greater focus to improve economies and health to meet the basic human rights to water and sanitation (Bain et al., 2014). Yet, studies relating to performance challenges of small piped water supplies (SPWS), used in smaller settlements or peri-urban areas, are limited. Available information for SPWS, often based on fast growing rural centers and towns, show that flow velocities in some areas are below the recommended minimum with some pipes not running full (Dadebo et al., 2023). Moreover, SPWS are noted to be 'disproportionately problematic' (Gunnarsdottir et al., 2020; Herschan et al., 2023) and are more often associated with waterborne disease outbreaks compared to larger water supply schemes (Moffatt and Struck, 2011).

Supply of high-quality water is gradually diminishing in most parts of Uganda including Mukono District (Bakamwesiga et al., 2022). This is partly due to low water pressure which leads to increased water contamination in the water supply system. Sufficient residual pressure should be maintained in water distribution systems, public standpipes, undulating terrain as well as in hydraulically remote and highly demanding sections (MWE, 2013).

The aim of this study was to investigate the impact of variations in water pressure on water quality and consumer acceptability in two SPWS of different ages. Using a case study of two SPWS in Mukono District, Uganda, of differing ages, the objectives of the study were to: i) measure water quality and pressure variations across each SPWS, ii) understand consumer satisfaction levels through collection and analysis of qualitative data iii) compare variations of water quality, pressure and consumer satisfaction between the older and newer SPWS iv) provide recommendations for improved water management of SPWS.

2. Methodology

2.1. Study area

The two SPWS schemes studied, Nakifuma and Kalagi are located in Mukono District; with 285 and 2267 water connections respectively. Nakifuma water supply scheme is an older scheme (2008) serving a smaller community of seven (7) villages in four management territories/zones compared to Kalagi water supply scheme (2018) that serves 51 villages in four management territories/zones. Production wells of both schemes are located near wetlands, and for Kalagi the wetland is surrounded by agricultural farmland. In both schemes, the water is manually dosed with chlorine using a bucket either in the production well and/or the collection tank.

2.2. Data collection

The study used qualitative and quantitative approaches to collect data on quality and reliability of water supplied, pressure and perception of operators, technicians, managers and customers/households connected to the existing supply. Sampling of study respondents were both purposive (operators, technical staff and managers) and random for households (connected customers to the grid).

In determining the sample sizes for study for each of the two schemes, firstly, the zones (territories) and then village, with high number of customer connections were purposively selected. In Nakifuma small water supply scheme, Kaama village in Kaama territory/zone has the highest number of piped water connections of 87 customers while Kalagi trading center in Kalagi territory/zone has the highest number of piped water connections of 100 customers in Kalagi water supply scheme. And secondly, the sample size for each of the study villages of 80 households for questionnaire administration determined to be adequate using Yamane (1967) formula, were randomly selected. However, sampling of households for pressure and water quality analysis were purposively done to select households connected along the distribution system and those towards the end of the distribution system. Structured questionnaires were administered to the 80 sample households with piped water connections to each of the two villages in the two schemes. Water commercial officer for each territory/zone selected together with local guides supported the research team in identifying households randomly selected for the study. A second set of questionnaires were also administered to fifteen (15) purposively selected key stakeholders who are directly involved in the operation and management of the two schemes. These included supervisors at the Ministry of Water and Environment, Mukono District Water Office, and technical operators of both the supply schemes. All questionnaires were developed to collect primary data on stakeholder perceptions on the variation of pressure and water quality in distribution networks in Nakifuma and Kalagi small water supply systems under Mukono District. All fieldwork data collection protocols were pretested for appropriateness and any improvements made where necessary.

Water pressure loggers and taps for providing the water samples were installed at selected points along the distribution networks of the two schemes (Fig. 1) and at points before the meters of selected customers.

To enable pressure measurements along the supply chain, sampling points at straight sections of the pipe network were drilled (permission was granted by management for a limited number of points in each of the SPWS) and pipe saddles installed on the pipes, while tee connections were created on the pipe network in sections with already existing tapings; (Fig. 2). A tee connection point was created at the meter points of the selected households. Over a period of two months a water Pressure Logger was installed every day in the morning when samples were to be collected and removed in the evening of the same day. The collection of pressure data was done three times on every sampling point for three different times and days of the week. Data recorded on pressure loggers

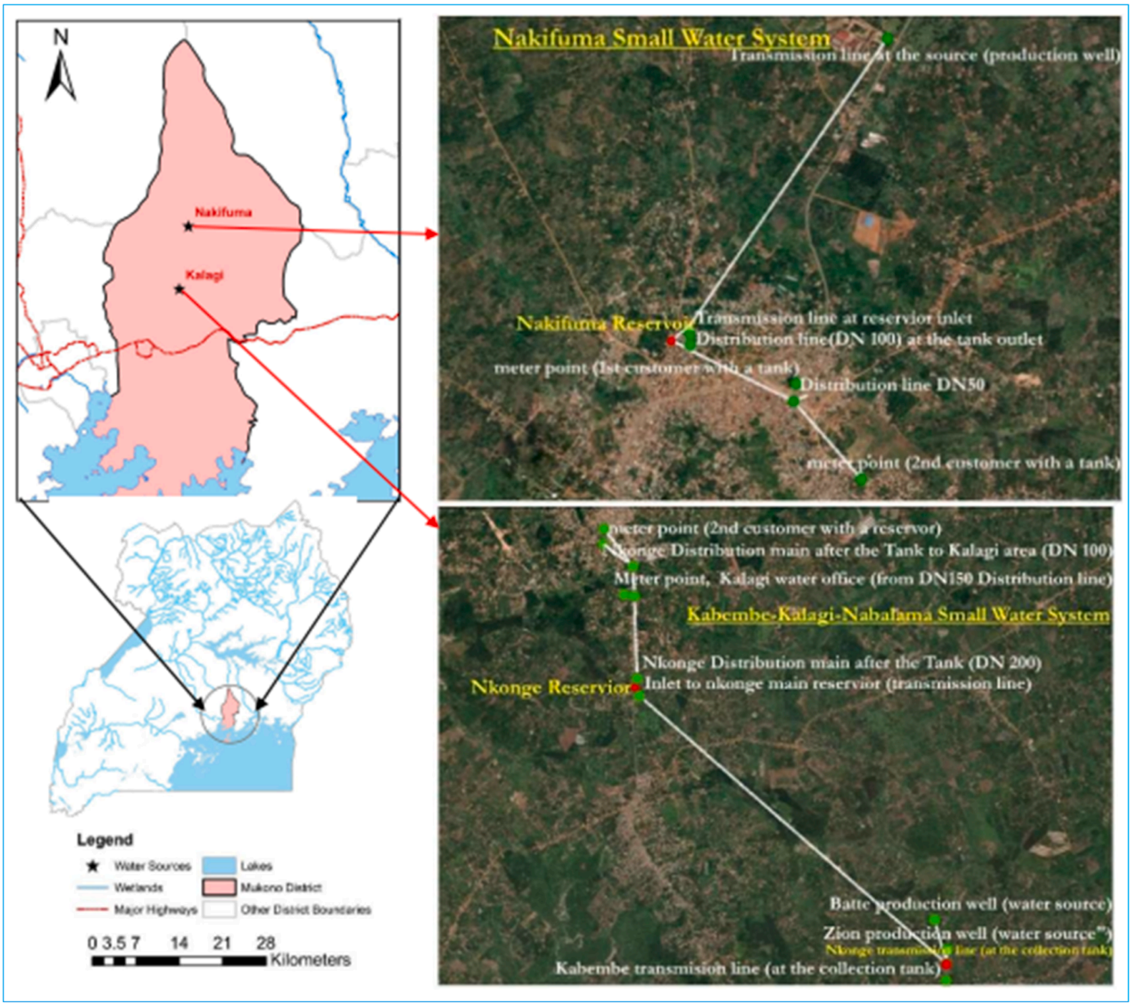

Fig. 1. Pressure and water quality sampling points in the two small piped water supply systems in Mukono - Uganda.

Fig. 2. Sampling point created on the DN100 pipeline with a pressure logger installed and tap point to collect water sample.

was extracted to a computer, using “Radwin view version 4.84″ software and analyzed using Microsoft excel.

Water quality measurements were carried out by identifying and installing sampling points in the sections created on the network chain and households, from the point at which water enters and leaves the treatment plant(s), collection tanks, and reservoir and up to the customers’ meter point. Water quality samples were also collected at every point where the pressure measurements were done in the network. Field and laboratory water quality analyses were conducted on water samples collected from different sampling points along the supply chain. The water samples were tested for common water quality parameters known to affect human health if consumed in water and continuously monitored by the regulatory authority; these included Turbidity, Total Coliform, Total Dissolved Solids, Apparent Color and Residual Chlorine. The water quality parameters assessed can provide a general indication of any variations in the physiochemical and bacteriological parameters of the water along the supply network.

Total Dissolved Solids, and Turbidity were analyzed in the field while Apparent Color, Total Coliform and Residual Chlorine were analyzed in the laboratory. Turbidity was measured in NTU using an electronic hand-held LaMatte meter (2020weTurbidmeter), and Total Dissolved Solids measured in mg/l, Electrical Conductivity was detected using a Portable Electro conductivity meter (ELE international). Palintest photometer 7500 water quality testing equipment was used to measure Residual Chlorine (mg/l). A platinum-cobalt standard methods was used to measure apparent color (APHA/AWWA/WEF, 1998). Total Coliforms were quantified (cfu/100 ml) in the laboratory using spread plate method with Chromocult agar media and plates incubated at 36 - 42 °C for 18–24 h following standard methods for examining water and wastewater (APHA/AWWA/WEF, 1998). All samples were analyzed within six (6) hours of arrival at the laboratory.

2.3. Data analysis

Statistical analysis was carried out using SPSS version 25 including frequency, mean, percentage, standard deviation, and Pearson's correlation coefficient. Data were first cleaned and processed before analysis for trends and results presented using MS excel charts. Qualitative data were analyzed based on grouped opinions from different respondents using MS excel top-level charts to deduce themes and relevant information that emerge from data collected through interviews with technical and non-technical respondents. Responses to a specific question from different respondents were all entered under the same column. Each question / column was then perused to draw common themes and relevant information on pressure and quality in study.

The qualitative aspect of study was given a favorable ethical opinion by the University of Surrey's ethics committee prior to commencing data collection (reference number FEPS 20–21 012 EGA).

3. Results

3.1. Physiochemical parameters

The results show a general trend in variation of physiochemical properties in the two small piped water supply schemes with most of the parameters deteriorating from the treatment/storage reservoirs to the consumer points while a few parameters show improvement along the supply network with reducing pressure in the pipes (Figs. 3 and 4).

From Figs. 3 and 4 above, similar trends are observed for Total Dissolved Solids. In the Nakifuma distribution system, Turbidity is fairly constant at 0.6 NTU and its mainly Total Dissolved Solids and Electrical Conductivity that change to a maximum of 114.9 mg/l and 243.6 μS/cm respectively. Relatedly Apparent Color reduces as pressure reduces from the source and again increases when the flow is increased from a pipe of internal diameter of 100 mm (DN100) to 50 mm (DN50), reaching a maximum of 30.7 PtCo in the distribution line with a pressure of 26.8 m. Total Dissolved Solids reduced to 108.5 mg/l and Residual Chlorine stagnated at 0.3 mg/l. In the Kalagi small water system, turbidity reduces with reducing pressure which may be explained by settlement of particles as velocity of flow of the water in the pipe reduces towards the final draw-off points.

Qualitative data from Kalagi small-scale piped water supply scheme indicated that the scheme has a long network and experiences prolonged periods of water rationing. At the outlet of the reservoir into the distribution pipe, the water pressure, TDS, Residual Chlorine and Turbidity recorded was 43.9 m, 644.5 mg/l, 0.3 mg/l and 0.5 NTU respectively. Water reached the customer meter point in DN20 pipe of the Kalagi network at a reduced pressure of 13.4 m, and increased TDS to 807.8

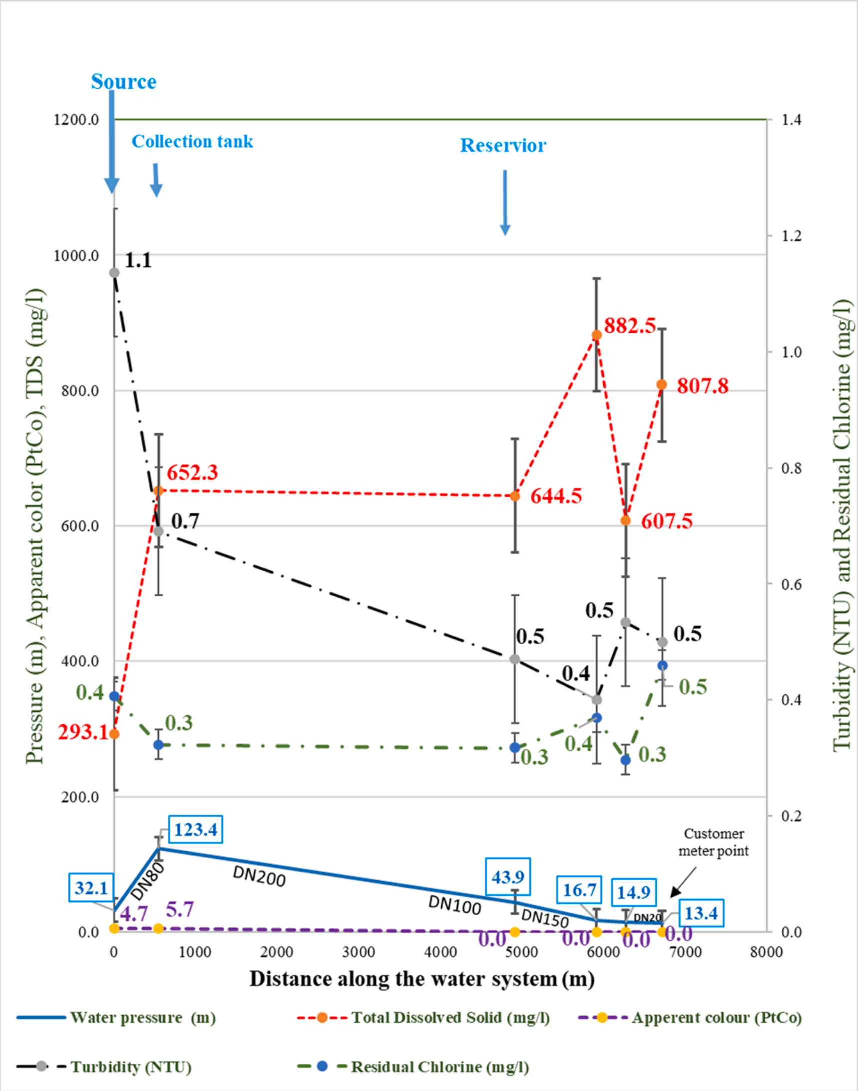

Fig. 3. Variation of water pressure and physiochemical parameters of water along the water supply networks of Kalagi small water system.

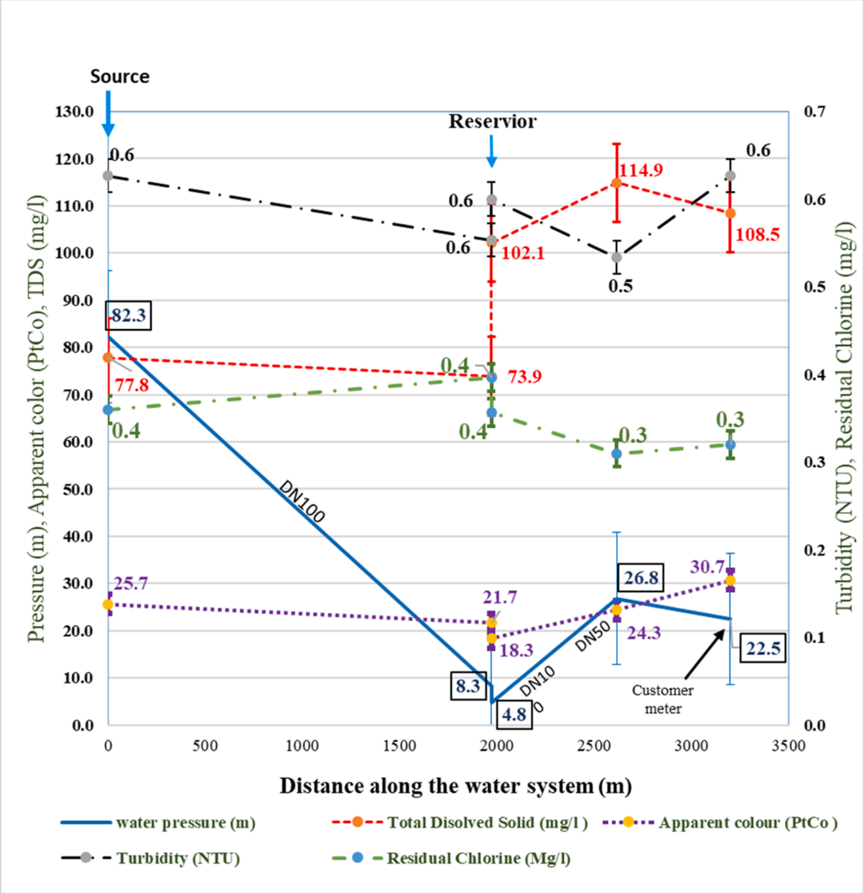

Fig. 4. Variation of water pressure and physiochemical parameters of along the water supply networks of Nakifuma small water system.

mg/l and Residual Chlorine of 0.5 mg/l was record.

Based on the observations, it can be inferred that Total Dissolved Solids (TDS) shows a relative variation with residual pressure in both the small old and new systems. However, TDS is notably lower in the small old water system and higher in the new system, with levels below 300 mg/l in the old system and ranging from 300 to 900 mg/l in the small new water system. Additionally, a decrease in pressure within the distribution networks led to a slight decline in turbidity in the new system ($p = 0.031$), while remaining relatively constant in the small old water system ($p = 0.951$).

In the network system, residual chlorine was recorded to reduce in both old and new small water system with a reduction in Residual Pressure. However, a small correlation with water pressure was recorded in Nakifuma ($p = 0.841$) as well as in Kalagi ($p = 0.392$) with low significance levels.

3.2. Bacteriological parameters

Results from all the sampling points show high values of Total coliform except in the transmission line from the production well in Nakifuma. Although chlorine dosing is done at both the production wells and/or collection reservoirs in both schemes, all samples taken from the Kalagi scheme showed some level of contamination as indicated by Total coliform counts (Fig. 5).

The high levels of Total Coliform in Fig. 5 demonstrate inadequate treatment and/or high levels of contamination of water during transportation from source to the final consumer. In Nakifuma water supply system, water is dosed with chlorine at the production well and as it enters into and leaves the reservoir to a DN100 HDPE distribution main at water pressure of 4.8 m, and Total Coliforms counts of 6203 cfu/100 ml is recorded. As water travels through the network, the pipe reduces to DN50, and water pressure increases to 26.8 m whereas Total Coliforms reduces to 821 cfu/100 ml. At the customers meter point in a DN20 pipe, the water pressure reduces to 22.5 m, while Total Coliforms increases to 1370 cfu/100 ml.

On the other hand, in Kalagi water supply network, water leaves the collection tank at pressure of 123 m and Total Coliform of 28,600 cfu/100 ml, then reduces 43.9 m at the reservoir tank with Total Coliforms raising to 35,067 cfu/100 ml. One thousand meters away, water pressure reduced to 16.7 m and Total coliforms increases to 40,850 cfu/100 ml in DN150 UPVC pipe. At 1354 m away after the reservoir, water pressure reduced to 14.9 m and Total Coliforms increases to 45,366.7 cfu/100 ml in DN100 pipe. At the customers meter water pressure is 13.4 m with a Total Coliform count of 63,800 cfu/100 ml.

3.3. Stakeholder perceptions

From the qualitative data gathered from the households, majority of the respondents (67 %, $n = 115$) reported that water is not always available in their area all the time, more in Kalagi (91 %, $n = 63$) than in Nakifuma (39 %, $n = 52$). Of those who reported that they do not have water available all the time, majority perceive the quality to be good, more in Nakifuma ($p = 0.005$) than in Kalagi ($p = 0.132$). Relatedly, the technical respondents in Kalagi indicated that water is always rationed in all the service zones to ensure that each zone receives some water in a week. The results also indicate that the older scheme has an operation and management team that has made use of operational data collected over years from treatment and distribution aspect of the scheme to improve their performance and service delivery over time, despite financial challenges. However, it was noted from the interviews with

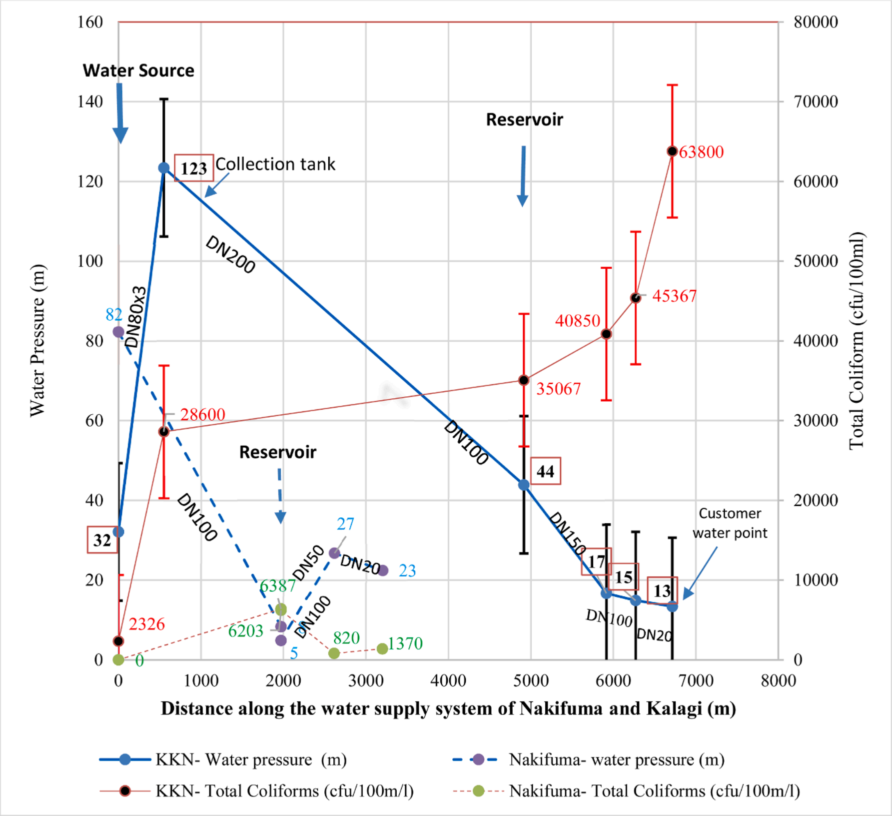

Fig. 5. Pressure and Total Coliform variations along water supply network in Nakifuma and Kalagi (KKN) small piped water system.

technical staff of Kalagi SPWS that training of operators and other technical staff in operation and management of small to medium piped water supply schemes is necessary to ensure high performance and realize the benefits of increased access to safe water.

Quote: *"We have the tools used by the operators"*

but

"We need these operators to be trained for some period" Kalagi technical respondent.

Whereas Kalagi is being operated and managed as a small-piped water supply scheme, it has coverage, water rationing and breakdowns in the pumping system affecting its performance which is much lower than for the older scheme. It's larger geographical coverage and high demand gives an opportunity to review their record for the few years in operation to make appropriate decisions to improve performance.

Results from the water samples taken from the networks and stakeholder interviews are discussed in the following section.

4. Discussion

4.1. Supply pressure and water quality variations

Analysis of both qualitative and quantitative data shows some comparable results on variations of physiochemical and bacteriological water quality parameters along supply network of two small water supply schemes of different ages. The results reveal deterioration in most of the physiochemical parameters measured from the points where chlorine is dosed up to where the water is collected by the households. Although most of the physiochemical parameters fall to within acceptable limits according to WHO guidelines for drinking water (WHO, 2017), Total coliform that was used as indicator organism falls outside the WHO guidelines; an indication of recontamination of the water during distribution. Rheingans and Moe (2006) noted that there a number of factors that affect water quality in distribution systems including pressure losses that may bring in microbial contamination as well as age of distribution systems that may make then susceptible to main breaks.

From the results, water residual pressure in small piped water supply network affects the quality of water in relation to Total dissolved solids. However, both systems recorded turbidity values ranging within the acceptable values according to WHO drinking water Guidelines, i.e., < 5 NTU (WHO, 2017). This implies that pressure does not significantly affect the Turbidity of water as it travels through small piped water supply network. In a study by Choi et al. (2014), the authors observed increased turbidity in the local water service distribution network with drastic change in water pressure. The difference noted in this study may largely be attributed to length of pipe network and flow pressure recorded in the small piped water supply schemes as compared to large piped water supply networks.

The study also confirmed that residual pressure affects the quality of water in terms of residual chlorine in a small water supply network system. In a related study by Hossein et al. (2013b), water pressure was noted to have a direct relationship with residual chlorine in a small water distribution system.

The results clearly demonstrate a higher level of contamination of water supplied in Kalagi network compared to Nakifuma which can be explained by several reasons expressed by respondents during both household (non-technical) and operator (technical) interviews. As noted in paragraph 1 of Section 3.3; in attempts to ensure that each zone in the service area receives some water in a week, frequent rationing of water in Kalagi leaves supply pipes with no pressure. This situation gives room for intrusion of some impurities into the water which would partly explain the higher values of both physiochemical and bacteriological parameters. Respondents interviewed in Kalagi rated routine flushing of pipe network to prevent blockage and deterioration of the quality of water supplied as moderate with frequent failures of pumping system due to power. This explains why the supply network have no pressure for some days causing settlement and accumulation of silts in valleys that are not usually flushed.

Generally, Total coliforms and water pressure had an inverse relationship in both the old (Nakifuma) and the new (Kalagi) small water system, but there were higher figures of total coliforms observed in the new system compared to the old system. Higher values of Total Coliforms at lower values of residual water pressures were detected in both systems. These findings imply that water residual pressure is a factor in determining the number of Total Coliforms in a supply network, in small water supply systems. The results therefore confirms to the study results which revealed that, pressure has an inverse relationship with bacterial growth in water distribution system (Hossein et al., 2013b).

Although results for the schemes show similar trends in variation of water quality with pressure along the supply networks, it is more pronounced in Kalagi than in Nakifuma. In all the parameters measured, the values in Kalagi are higher than in Nakifuma except for apparent color; despite Nakifuma being an older scheme.

4.2. Reliability of supply in the distribution network

Despite the ages of the small piped water supply scheme, management has shown to be key in ensuring reliable supply. Milman et al. (2021) urges that well-performing water suppliers are characterized by a strong knowledge base, human and organizational capacities, with a culture of continual improvement, functionality and long-term sustainability of water systems. Although household may try to cope with un reliable access, by altering their daily routines, consume less water, or identify and use alternative sources of water, these will still compromise with the full benefits of access to safe and adequate quantity of water (Smiley, 2016; Pahl-Wostl et al., 2013). The more recent schemes need capacity building to improve reliability as the case with large piped water supplied schemes (MWE, 2018).

The study has revealed that optimal and continuous pressure safeguard quality and improve access but this can only be achieved under good management practices. The bigger the system the more problematic its management may be (Gunnarsdottir et al., 2020; Herschan et al., 2023). Where SPWSs are growing or have overgrown its management structure as small piped water supply scheme, it may be necessary to restructure it as a medium or large water piped supply system, to ensure that the people served receive safe and adequate quantity of water to meet their basic human rights to water and sanitation (Bain et al., 2014; Shrestha et al., 2017).

4.3. Proposed model to ensures safe water and adequate residual pressures

The data collected and discussed shows that pressure varies in different ways with different parameters of water quality as it's supplied in the network for both new and older small-piped water systems. The results were compared with international standards and it showed that some values where not meeting the desired minimum standards recommended by World Health Organization (WHO, 2017).

To achieve the desired standard, a model (Fig. 6) is proposed and can be adopted in realizing an optimal pressure and water quality in small piped water supply scheme.

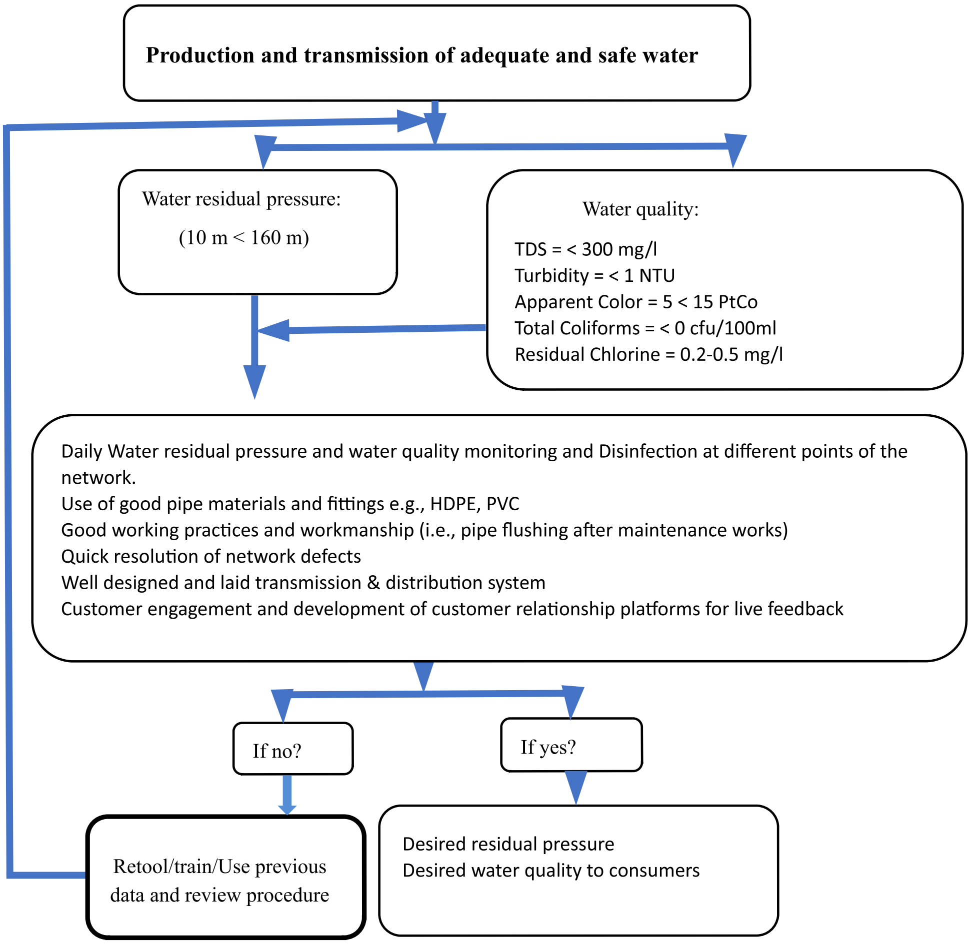

Fig. 6. Proposed model to attain the desired residual pressure and safe water in small piped water system.

Improvements to the systems should be made to ensure that the water pressures supplied is between 10 and 160 m head of water in order to prevent occurrence of network defects which may lead to contamination. It is also important to ensure the quality (TDS, Turbidity, Apparent color, Total Coliforms, and Residual Chlorine) of water supplied meets the standards as guided by WHO (2017), for drinking water and should be maintained up to the final consumer. To achieve the pressure desired in the small water supply system, the network, including the reservoirs should be well designed and laid with good pipe materials (such as High-density polyethylene - HDPE, Polyethylene - PE). Good working practices, workmanship and quick resolution of any network defects should be employed to prevent any pressure drop and intrusion of contamination into the water system as is recommended by regulatory authorities (MWE, 2013). Points of monitoring and disinfection in the water network should be created on the network to allow disinfection of water whenever and after any maintenance works are done. For example, at points with major changes in pipe diameter within the distribution network, at points in low laying areas and at every reservoir. Points for water pressure monitoring should be created on the pipe network system and include pressure gauges to measure, monitor and manage pressure variations in the water supply network. A customer engagement and relations platform should be available and continuously maintained to receive live feedback from customers and such data and information used for better decision making and quick response to any occurrence to network defects to avoid contamination of water. Continuous evaluation and review of the operational performance and consumer feedback aimed to improve service deliver will minimize the possibility of delivering unsafe water that may jeopardize acceptability and health of the consumers (Chenoweth, 2008; Moffatt and Struck, 2011).

5. Conclusion and recommendation

Pressure variations in water supply network influences the quality of water supplied to the households in the water system in addition to other factors that leads to deterioration of water quality at the household. Water residual pressure in small-scale piped water supply networks cause minimal variation of water quality as low pressure makes the network prone to intrusion of impurities. However, regardless of a system's age the variation is more pronounced in networks that experience prolonged rationing where pipes stay under no pressure for some days.

The available evidence indicates that adopting efficient management strategies that utilize historical data to ensure optimal residual and continuous pressure can improve performance of SPWS to meet acceptable standards. Decisions derived from relevant operational data of previous experiences, while embracing capacity and skills development of technical personnel through training and other technical supports, is essential for future improvements of SPWS. Additionally, in response to larger geographic coverage and growing demand, there might be a need to consider reorganizing and managing small piped water supply schemes as medium-sized or even large-scale supply schemes.

CRediT authorship contribution statement

Kenan Okurut: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition. **Jamiru Ntumwa:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – review & editing. **Anne Nakagiri:** Formal analysis, Writing – review & editing. **Jo Herschan:** Methodology, Writing – review & editing. **Aime Tsinda:** Writing – review & editing. **Rosalind Malcolm:** Writing – review & editing, Funding acquisition. **Dan J Lapworth:** Writing – review & editing. **Kathy Pond:** Methodology, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

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

Data availability

The data that has been used is confidential.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2023.100771.

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