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Managing non-revenue water in Mwanza, Tanzania: A fast-growing sub-Saharan African city

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A B S T R A C T

High non-revenue water (NRW) and unreliable water supply services are major challenges in operations of the water infrastructure of most fast-growing cities in developing countries. In this study, an analysis of the existing distribution network was carried out to investigate its performance concerning water loss reduction and system improvement. A high percentage of NRW (50%) was found in a selected district metering area (DMA) compared to the city's entire network (37%). About 87% of the NRW was contributed by real losses in the DMA, while about 52% of the nodal junctions had pressure above the recommended thresholds. The high pressure was responsible for the observed leakages and pipe bursts in the DMA. Optimization of pressure by using pressure-reducing valves as well as changing the network topology minimized the potential leakages to 46%. Also, flow velocities in about 83% of the pipes were found inadequate leading to poor water quality due to water stagnation. Low velocities were due to oversized indicating incidence of unplanned spatial and temporal expansion of the distribution network. This study, therefore, revealed that a comprehensive zone by zone assessment of water distribution network can improve the management of non-revenue in unplanned urban areas which is in line with ensuring the availability and sustainable management of water and sanitation for all.

Introduction

Many Sub-Saharan African cities have an old water supply distribution network characterized by high non-revenue water (NRW) that far exceeds the recommended limits for sustainable urban utilities [33]. Besides the old water infrastructures, the African continent's rate of urbanization soared from 15% in 1960 to 40% in 2010; and the population is projected to reach 60% by the year 2050 (Dominguez Torres, 2010 [8]). While the continent's population has drastically increased over

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the last decades, urban infrastructure including water supply infrastructures experienced limited improvements [24]. Many cities experienced urban sprawl and drastic population growth, leading to the unplanned or organic expansion of their water supply network infrastructures. The resultant 'organic' water distribution network is the main contributor to any city's high NRW [7]. Ensuring the availability and sustainable management of water and sanitation for all as enshrined in the sixth Sustainable Development Goal (UN, 2010) should be a national priority for most developing countries including those in Africa especially. According to the International Water Association (IWA), NRW results from apparent losses (e.g., unauthorized consumption, data handling errors, and customer metering inaccuracies), unbilled authorized consumption, and real losses/leakages (US EPA, 2000). The NRW threshold for well-performing water utilities is considered to be about 23% (Singh et al., [28]. However, most urban water utilities in Sub-Saharan Africa have NRW values higher than 23%. According to Tanzania Energy and Water Utilities Regulatory Authority (EWURA), a national NRW average is about 38%; which is much higher than the set national benchmark of 20% [9]. Despite the financial constraints of many Sub-Saharan African countries, the annual water revenue loss is estimated to be about 1.4 billion USD. However, most African cities are yet to develop credible plans to recover the amount of water lost through their old and unplanned distribution networks. The results from this preliminary study can be of help to many rapidly growing cities to understand the best ways of managing the NRW in an organic expansion of water distribution network by integrating it with commonly suggested approaches.

Various studies have indicated that controlling water loss and managing system operations in an 'unplanned' water distribution network is complex, and it is a major contributor to non-revenue water in urban areas [27][[nullM]18,21]. For instance, in the Kampala city of Uganda, the original network topology over-time grew into a 'spaghetti' network, which increased the percentage of non-revenue water in the area [21]. The spaghetti network was the result of the unplanned expansion of the distribution network, where the utility tried to cope with the city growth. Other factors that contribute to the high-water loss in sub-Saharan Africa are the old infrastructure network and poor management of system pressure [12,13,23]. The old networks often experience regular pipe bursts and leakages that increases the amount of non-revenue water. Although the old network requires regular performance assessment, timely repairs, and proper management of population expansions, these however are not given the needed attention by most water utilities in sub-Saharan Africa [25]. Most African water utilities could benefit from performance assessment and modelling of their old Water Distribution Networks (WDNs) as an important step in managing non-revenue water in such contexts [16]. To do this requires access to real-time data such as pressure heads and flow rates. Despite the absence of or inadequacy of Supervisory Control and Data Acquisition (SCADA) systems in most of the water utility companies in Africa due inadequate capital for its investment, performance of hydraulic behaviours of water network systems are still be carried out manually.

Flow rate is one of the most important measurements which an operator uses. This measurement provides information on the detention times in tanks, flow between various processes or sections of a distribution/collection system, chemical feed rates, amount of water treated/pumped, costs of treatment, and the need for system expansion. However, most water utilities do not collect real-time water supply data [11,22]. This tends to hinder the progress in approaching the management of non-revenue water resources effectively; due to an unclear understanding of the network topology of these areas.

Several studies in sub-Saharan Africa have shown that, real water losses/leakages are the main contributor to the high non-revenue water resulted from pipe bursts due to high pressure and old pipes [12,13,21]. So the determination of components of non-revenue water and operational pressure of the distribution network is of high importance. To maintain system pressure at recommended levels, some studies suggest the application of pressure-reducing valves (PRVs) as a tool for pressure management in the distribution network [10,16]. Herein this study, the importance of PRV optimization has been emphasised. In analysing the performance of the existing systems and predicting the outcomes of the interventions, a computational simulation model can be applied to forecast the future system conditions [14].

One of the pressure management studies in sub-Saharan Africa has suggested its integration with hydraulic model simulations as a tool for effective water loss reduction [16]. Due to limitations of networks and local conditions in sub-Saharan countries minimum night flow (MNF) analysis is recommended as the best method providing meaningful results in the determination of real water loss in the system [3]. In MNF the three items that are taken into consideration include flow and pressure measurement tools, night water consumptions, and average system pressure. However, most of these studies have not assessed the impact of change in network topology due to unplanned or planned networks on non-revenue water.

This study used a hydraulic simulation model (EPANET 2.0 software)[null_] [15] to assess potential management options for reducing the levels of NRW in a fast-growing city in Tanzania. Although hydraulic simulation of water distribution networks is a well-established technique, a limited number of studies consider the impact of unplanned urban water infrastructure expansion concerning high water loss. Existing research on unplanned expansion mostly assessed the potential of reducing water loss through pressure management [12] and or pipe replacement [13]. Also, most studies on planned water distribution networks do not consider the impact of changing the network topology as one of the strategies for water loss reduction. This study posits that effective non-revenue water management can be realized if water pressure management is coupled with a change in the network topology. This approach is likely to be suitable for managers with a fast-growing water distribution network. Mwanza city is one of the fast-growing cities with high non-revenue water in Tanzania was selected for the analysis. The reduction in non-revenue water losses will contribute towards increasing the populations' access to improved adequate and sustainable quality water supply towards achieving the sustainable development goal 6 and the African Union's Agenda 2036, Aspiration 1, Goal 7 [31] [nullY] (United Nations, 2018).

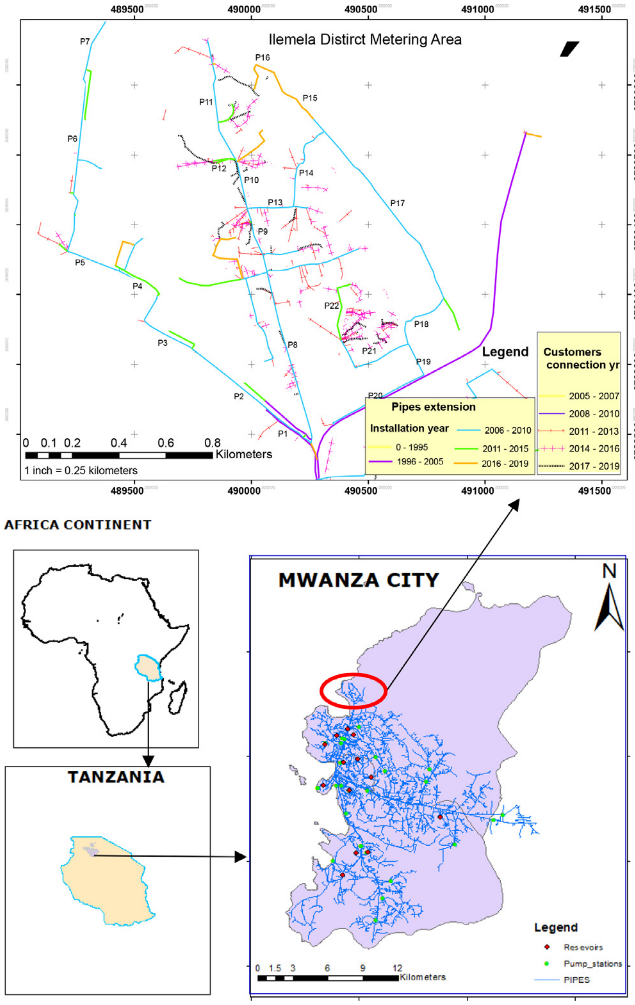

Fig. 1. Map of an existing distribution network of Mwanza city and the Ilemela DMA in Tanzania.

Materials and methods

Study area

The study was carried out in Mwanza city (Fig. 1); which lies on the southern shores of Lake Victoria in the north-west part of Tanzania. In 2012, the city population was estimated at 905,473. The city's water distribution network currently serves about 74,314 customers. Using the average number of people per connection is 15.5 [4], the total number of customers in Mwanza was estimated at 0.77 million in 2015 and 1.15 million during this study. The city water is drawn from the Capri-point intake station on Lake Victoria, treated, and then conveyed to customers through a 789 km long transmission and distribution pipelines.

The average daily water production is 73,233 m^3 due to limitation of the capacity of the Water Treatment Plant (WTP) but the daily water demand is estimated at 116,575 m^3 far exceeds supply/water production capacity. The above-mentioned water transmission and distribution systems have grown rapidly into unplanned areas which caused 'organic' expansion of the network that is suspected to led to high water losses and the developed unknown hydraulic behaviour of the system as a result of poor management of the changes in network topology. For instance, before the year 2000, the total length of the network was only 160 Km. However, from 2000 to 2019, the network expanded from 220 Km to 367 Km. Despite the water demand being greater than the production, the utility does not practice water rationing. Water distribution within the network is determined by the nature of elevation of the areas (hilly, flat or low ground levels), pipe sizes, water demand and consumption patterns which has led to higher elevations areas supplied with low-pressure water, no flows or intermittent supply, while lower areas receive 24 h of water supply. As a result of this operation, Mwanza city is one of the Tanzanian cities with very high levels of NRW. For five consecutive years (2012 to 2017), the city NRW was at 42%, 41%, 41%, 38%, and 37% respectively.

Table 1
Characteristics of major junctions and pipes for Ilemela DMA.

Junctions data			Pipe data		
Node ID	Elevation (m)	Base Demand (m^3/d)	Link ID	Length (m)	Pipe size (mm)
J-1	1140.00	49.11	**P1**	382.0	200
J-2	1147.20	63.51	**P2**	330.8	200
J-3	1145.27	25.83	**P3**	345.8	200
J-4	1154.37	36.63	**P4**	250.9	200
J-5	1184.64	98.79	**P5**	220.3	200
J-6	1189.31	22.23	**P6**	815.6	200
J-7	1184.05	22.71	**P7**	223.2	200
J-8	1196.65	19.59	**P8**	801.1	200
J-9	1149.10	21.03	**P9**	289.3	200
J-10	1180.41	27.27	**P10**	217.3	200
J-11	1150.71	21.99	**P11**	537.4	200
J-12	1151.98	14.07	**P12**	183.4	50
J-13	1160.69	51.99	**P13**	196.1	75
J-14	1168.19	26.55	**P14**	386.3	75
J-15	1181.72	42.15	**P15**	170.5	75
J-16	1170.20	39.03	**P16**	249.1	40
J-17	1142.99	13.35	**P17**	885.1	75
J-18	1144.71	13.35	**P18**	303.1	75
J-19	1152.09	13.35	**P19**	219.3	75
J-20	1170.59	13.35	**P20**	341.8	75
J-21	1170.81	13.35	**P21**	380.6	75
J-22	1151.46	13.35	**P22**	291.2	50
J-23	1147.77	13.35			

For this study, a small area (part of the city water network) called Ilemela District Metering Areas (DMA) was selected for measurements and analysis. It was selected because of its reported high number of pipe bursts and leakages observed during field works and uneven pressure distribution concerns. The area was also selected because it can be hydraulically isolated. It has 1004 customer connections, 13 km of distribution network, and it is mainly a residential area with few hotels and day schools; and almost no night clubs (Figure SM1). The topology in this layout (*Figure* SM2 and *Table 1*) shows a dominance of small but long ('spaghetti') service lines and fewer main distribution pipe lines. The limited number of secondary distribution pipelines in the area could be attributed to the formation of a spaghetti-type of service lines. The network topology of the selected DMA is a dead-end type (tree-structured) with the disadvantage of leaving a large area isolated during leakage repairs and high-water stagnation, unlike the looped type WDN.

The Ilemela DMA has a continuous water supply, a relatively new network, and its WDN topology can easily be isolated. The characteristics of the DMA network layout in Figure SM1 are shown in Table 1. The table shows the elevation difference between the lowest and highest points is about 56 m. The elevation difference may be having a high impact on operational pressure variations. Also, the pipe sizes are bigger than the base rate demand which can affect the flow velocity in pipes.

Flow and pressure measurements

Flow and pressure measurements were carried at various locations as shown in Figure SM3 in order to determine the hydraulic behaviour of the water network system. Ultrasonic flow meters for liquid model Fluxus F601 were installed at the outlet of the reservoirs to determine the flow rates and derive the demand multipliers representing water consumption patterns. The average customers' consumptions for twelve months were deduced from the utility billing database and used to determine the base demand. Ultrasonic flow metre model Fluxus F601 was also installed at the inlet of the DMA to record the amount of water entering the system. Seven locations with different characteristics of elevation and distance from the inlet were identified and installed with pressure loggers' (model XiLog + 2i). Using the collected data, a model of the WDN was built in EPANET 2.0 simulation software (Kanakoudis and Tsitsifli, 2012). The system operation was compared with the field data for the required residual pressure at junctions in comparison to the service, and minimum and maximum head thresholds. The residual pressure head thresholds at the junctions were assessed in three modes: *service pressure*, the *minimum* and *maximum pressure* [26]. To assess the performance of the selected water distribution network and the amount of non-revenue water, two parameters (flow and pressure) that describe the hydraulic behaviour of the system were analysed.

Assessment of the Ilemela DMA non-revenue water

The Ilemela NRW was computed as the difference between the amount of water entering the DMA and the total water consumed by customers. Daily Real Loss Volume (DRLV) was computed by using Eq. (1) as proposed by [6].

$$DRLV = Q_{MNF} \times \sum_{i=0}^{24} \left(\frac{P_i}{P_{MNF}} \right)^{N1} \tag{1}$$

Where DRLV is the daily real loss volume; Q_{MNF} is the average minimum night flow rate; P_i is the average pressure in observed points for each time t; P_{MNF} is the average pressure between 0300 and 0500 h; $N1$ is the flow exponent;

The Minimum Night Flow (MNF) is defined as the summation of leakages and legitimate customer night use was determined by taking an average of the minimum flow for the 24 h measured over a period of 11 days at the inlet of the DMA. The flow metre and pressure logger were installed at the inlet pipe to the DMA and recorded the flow and pressure hourly variations.

The minimum flow during early mornings was observed between 0300 and 0500 h where the pressure was at its maximum and the consumption was minimum. Since there were no major night activities (e.g. night clubs) at the site during the study, legitimate night water use was assumed negligible. The flow exponent (N1) was estimated based on the flexibility of the materials of the existing pipes which were made of uPVC and HDPE materials according to as-built drawings found in the study area.

A water audit of the Ilemela network was conducted following the International Water Association (IWA) standard water balance method of the bottom-up approach using field data measurements and computation of real losses [19,32]. The four main components of urban water use i.e. *billed authorized, unbilled authorized, apparent losses*, and *real losses* were determined from field data.

Computational modelling, model calibration and hydraulic analysis

The EPANET 2.0 software was used in the study for hydraulic analysis and simulation as well as prediction of the impact of installing pressure-reducing valves (PRV) on the level of non-revenue water of the DMA. The measured pressure and flow rates were used to validate the model. To ensure the model matched with the real system conditions, calibrations were done considering field data, location, and time of measuring pressure and flow rate data as shown in Figure SM4. Since the selected network formed part of the entire system, the operations of the entire city network was monitored to identify any unusual variation in the obtained data. The measured flow rates and pressures at the selected junctions of the real water distribution networks (WDN) were compared to the same junctions in the simulated model for mimicking the real conditions.

During the model simulation, the minimum pressure head threshold was assumed based on local standards of minimum pressure requirement firefighting of 15 m. The maximum pressure head (H_{max}) set was at 60 m beyond which the system was assumed to be on a higher side. Thus, the operational or service head (H_s) was ranging between the minimum and maximum pressure for the satisfaction of water demand at any junction. This was used in determining the leakages and pipe bursts within the system. By using Eq. (2), the satisfactory system operation was determined by checking the availability of required residual pressure at junctions (Gupta and Bhave, 1994; [26]). Modifications of flows and pressure were done using algorithms procedures explained in Figure SM5.

$$\boldsymbol{Q_{supplied}} = \begin{bmatrix} 0\ (\boldsymbol{no\ flow})\, for\ H > \boldsymbol{H_{max}} \\ \boldsymbol{Q_{j,req}}(\boldsymbol{adequate\ flow})\ for\ H \geq \boldsymbol{H_s} \\ \frac{\boldsymbol{H-H_{min}}}{(\boldsymbol{H_s-H_{min}})^{0.5}} * \boldsymbol{Q_{j,req}}(\boldsymbol{partial\ flow}) \\ 0\ (\boldsymbol{no\ flow})\, for\ H < \boldsymbol{H_{min}} \end{bmatrix} \tag{2}$$

Where $Q_{supplied}$ is the quantity of water supplied to a node; H_{max} is the maximum pressure head at the node; H_{min} is the minimum pressure at the nodes; $Q_{j,req}$ is the required/ demand flow to the node; H_s is the operational pressure head;

Results and discussion

Contribution of existing network topology to non-revenue water (NRW)

Key components of non-revenue water (NRW)

Fig. 2 shows a pictorial presentation of the water balance of the Ilemela case study area. It gives a summary of the major components of billed and unbilled water losses, which indicate that 87% of the water is lost through real leakages and no unbilled authorized consumption was found. The amount of NRW in Ilemela was estimated to be ~50%. The computed NRW was much higher than the average of 37% reported for the entire city [9]. This NRW was also found to be much higher than the 20% limit for Tanzania's water authority and the recommended 23% value for well-performing water utilities in developing countries. Furthermore, 87% of real water losses were due to pipeline leakages and frequent pipe bursts (as observed during network inspection) associated with poor operating conditions. The main contributing factor to this high non-revenue water loss is associated with the existing water distribution network topology and operating conditions.

A summary of the components of NRW in the study area compared with the entire city water supply network for leakages (real loss), apparent loss, and billed values concerning the total water supplied and NRW are shown in Table *SM6*. The water lost through leakages is about 44% of the total water supplied.

From the above analysis, conducting detailed zone by zone assessment thus provides better insights into the contribution of different areas of the distribution network to the city's overall NRW. Each zone may have a different network topology and other conditions which may vary in terms of factors contributing to non-revenue water. This approach thus allows the utility agency to identify priority areas for interventions. Hence, the zonal values can be used to develop appropriate strategies for NRW reduction in the city, which will significantly reduce the operating costs of the water utility agency.

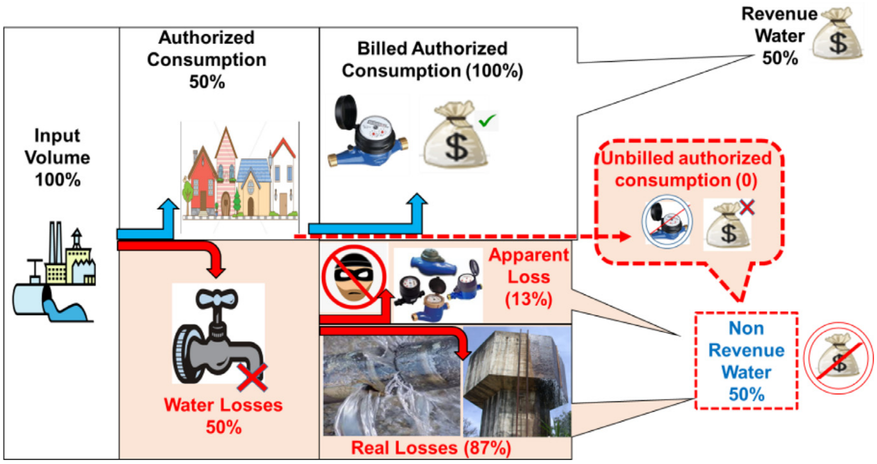

Fig. 2. Pictorial presentation of the water balance of Ilemela DMA.

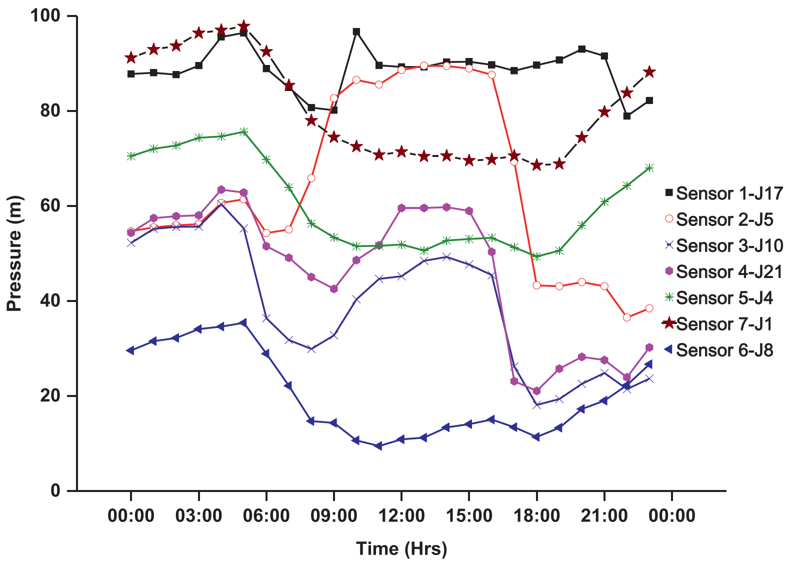

Fig. 3. Average hourly pressure variation at seven different locations within the study area.

Flow and pressure variations

Seven sensors were used to measure the head pressure at selected junctions of the Ilemela DMA. The results of the 24 hours' average pressure variations shown in Fig. 3 indicate that there is a big difference (*recorded values of ~70 m*) between the measured junctions (J-1, J-4, J-5, J-8, J-10, J-17, and J-21). The sensors also showed different hydraulic behaviours in the network system within the Ilemela DMA: some parts had very high values while other parts had very low values. From Fig. 3, some parts of the areas receive residual pressure below 15 m while others received pressures above 60 m. Only two areas represented by sensors 3 and 4 received pressure values within the range of service head or full flow mode of 15–60 m. Sensor 2 had higher pressure while sensor 5 had lower values than recommended from day hours of 0800–1700 hrs and night hours from 2100 to 0800 hrs respectively.

The system thus showed two different patterns of hourly pressure variations for sensors 1, 5, 6, and 7 and sensors 2, 3, and 4. This could be due to different water demand patterns by the customers and their cultural behaviour in water consumption. Also, abnormal high flows due to pipe leakages might have caused hourly pressure variations. However, operating a WDN at a pressure head above 60 m is not recommended as it increases leakages and real losses in the system [30]. According to the study done by Harawa et al., [12] in Lilongwe, Malawi, high pressure ranging from 50 to 80 m was the major reason for the high percentage of real loss (86%). Also Hoko & Chipwaila, [13] in their study in Zomba city, Malawi found that a high percentage of NRW was contributed from the real loss ranging from 58 to 81% which were the results of high pressure within the system. The findings of this study show comparable outcomes to the two researches done in Malawi. Another research conducted in the Mabelreign and Glen View suburbs of Harare, Zimbabwe found that high percentages

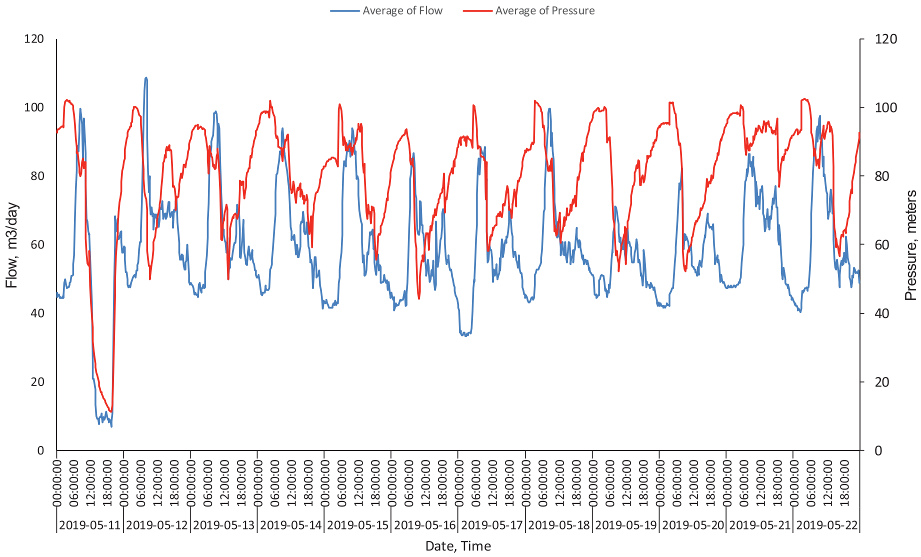

Fig. 4. Flow rate and pressure entering the DMA showing peak and minimum values.

(85.1% and 85.2%) of real loss was due to the old pipe network of about 47 and 34 years old respectively [23]. However, this factor does not apply to this study since the network under consideration is less than 20 years old.

Analysis of the daily flow pattern is presented in Fig. 4. The normal trend of water consumption with two peak flows was obtained in the morning and evening and low flows in the early morning and late night hours. However, there were some days that the DMA was receiving less water even during peak hours as shown on 19th, 20th, and 21st because there was apparently no water in the entire city network. Since this area is mostly residential, its night consumption was expected to be negligible. However, a substantial amount of flow above 40 m^3/h was recorded during early mornings between 0300 and 0500 h. This is an indication of leakages within the system. Karadirek, et al., [16] also observed in another study that high MNF is an indication of a large amount of real water loss.

Velocity distribution within the water distribution network

The existing distribution network model was simulated to obtain the pipe velocities as shown in Figure SM7. The velocities of the water flowing in the pipes were found to be below the minimum recommended value by the national design manuals of 0.6 m/s for the distribution network except for pipe numbers 13, 14, and 17. Thus, 86% of velocity results were lower than the specified range of acceptable velocities. The installed pipes were also bigger than the current water flow in the DMA. As a result, the pipes store water in the network; thereby increasing the system pressure and water stagnation. Therefore, the small service lines connected to big pipes worked as orifices that released water to users. This behaviour is also likely to result in water stagnation in the pipeline network of the DMA and hence influence the water quality. Kimbell et al., [17] indicated in their study that, when the velocity of the water in the system is low it may create depositions and deteriorate the water quality. Albert, et al. [2] however, found that high velocities within the system may reduce water stagnation hence eliminates chances of any microbial growth and depositions. Abnormally high velocities in the pipeline systems may be due to under-sized pipes installed in the sub-zones of the water supply schemes [1]. Therefore, the low velocities found in this study could be attributed to over-sized pipes.

The whole left branch of the WDN located along the lake shores has a low population and flow velocities but high pressure. They also comprised of bigger pipe sizes mostly 200 mm in diameter. Only a small section of the right has high pressure and low velocities. Highest and low values of the two variables do not depend on each other in the system. Low flow velocities could be a result of low average daily demand of the population served compared to the capacity of the existing system. The analysis shows the importance of integrating uncertainty of town growth in designing WDN which could incorporate future random demand expansions. This method has shown the impact of management of the change of the network topology due to the unplanned expansion of network on NRW reduction.

Model calibration

The calibration of the network model showed that a combination of pressure sensors with similar patterns i.e. 1, 5, 6, and 7 (*junctions J-1, J-4, J8, and J-17*) respectively had strong model fitness (*~0.993 correlation between means*) compared to calibrations that combined all seven sensors (*0.876 correlation between means*). This gave an indication of possible large water consumers or unknown connections in the network system. In view of this, site investigation and analysis of various consumptions including several measurements in different seasons were proposed for the model adjustments in order to reduce model fitness errors. However, during the field measurements, there were system interruptions due to unscheduled power

Table 2
The simulated pressure values in metres for the four set-ups of PRVs.

Node	Before installing PRV	Installing one PRV at the entrance (Scenario 1)	Installing two PRVs for each branch (Scenario 2)	Installing two PRV and change water flow direction for some links (Scenario 3)	Installing two PRV and loop the entire network (Scenario 4)
J-1	82	80	37	37	79
J-2	75	73	29	29	72
J-3	77	75	31	31	74
J-4	68	66	22	22	65
J-5	37	35	35	35	35
J-6	33	31	30	30	30
J-7	38	36	35	35	35
J-8	25	23	23	23	22
J-9	73	71	70	27	70
J-10	38	38	38	38	38
J-11	61	66	65	66	67
J-12	58	65	64	25	67
J-13	45	53	52	53	54
J-14	36	45	44	45	46
J-15	22	31	30	31	32
J-16	34	43	42	43	44
J-17	79	77	34	34	76
J-18	77	75	32	32	74
J-19	70	68	25	24	67
J-20	33	43	42	43	43
J-21	33	42	42	42	43
J-22	60	65	65	25	66
J-23	74	72	29	29	71

cuts and repairs at various points which might have contributed to these errors. Hence, system monitoring during the measurement process is very essential for calibration corrections. The model simulation has proven to be one of the approaches which can be applied in assessing the impact of unplanned water distribution network of NRW reduction strategies.

Performance optimization of existing water distribution network

The junction analysis detected some nodes with higher leakage rates and different hydraulic behaviours. To improve the hydraulic conditions of the existing network, link-pipes joining the four nodes J-9, J-11, J-12, and J-22 were added which made it possible to change the DMA to a looped network. Hence, changing the WDN topology (connections taping points) by adding secondary distribution pipes helped to reduce the 'orifice-like' operation of the service lines, since it had low capacity to withstand high flows and pressures. This approach also reduces leakages from the small-sized but long-spaghetti pipelines in the area and ultimately reducing water stagnation in the entire distribution network. Furthermore, this changes the network topology allowing more water to be allocated to areas with high demand as well as facilitating pressure and flow adjustments to the random expansion within the network. The simulation indicated that some nodes could receive less flow if they continue to be supplied from the existing setup. However, these nodes showed best results when shifted to the higher-pressure supply zone than the existing supply direction. This revealed that one DMA could require two different pressure settings/zones in order to ensure adequate pressure and flow in the system. It emphasizes the idea of sub-zone establishment for areas of high-pressure variations so as to demarcate areas with equal range of pressure supply zones. The objective function of leakage minimization was easily achieved by optimizing the location of pressure-reducing valves, number of PRVs and pressure settings in the network. The results of four scenarios developed i.e. installation of (a) one PRV at the common entrance pipe; (b) two PRVs set differently each at the main two entrance pipes; (c) two PRVs and change the water flow direction by adding 2 links; and (d) two PRVs and change the flow direction by looping the entire network are shown in Table 2. In scenario 1, 2, and 4 part of the system still had high pressures above 60 m which reduced leakages to ~95%, 81% and 93% of the existing real water losses respectively. Scenario 3 resulted in average pressure within the recommended values for all parts of the network which proved to be the best scenario in terms of leakage reduction.

The best scenario of PRV optimization was to install two PRVs each in the existing branches of the distribution network which will effectively change the flow directions/network topology. The intention was to increase or decrease the nodal demand depending on which part of the network had values of pressure and flow below the threshold in this study. The simulated pressure indicates that using the pressure reduction technique together with network topology modification can reduce water leakage up to about 46%. Similar studies by Harawa, et al. [12] and Monsef, et al. [20], also suggested using PRVs as one of the measures to achieve the best results in reducing real-loss in the water distribution network. The optimization scenarios that considers location, quantity, and pressure settings of PRVs as the decision variables are of paramount importance [5,16].

Installation of pressure reducing-valves in the system reduced high pressure which may deteriorate the lifespan of the infrastructure. Despite preventing pressure-dependant losses and pipes lifespan, PRVs help in adjusting pressure settings during pressure-deficient conditions that may be caused by increasing water demand [29] [null]](*Sivakumar and Prasad, 2015*). During excess demand periods, the pressure-reducing valves may be regulated to prevent partial or no flow conditions that may arise within the system. Although PRV applications have been studied by many researchers, its optimization has been emphasised herein this study.

Conclusion

In the study, techniques on the management of the non-revenue water have been tested on selected unplanned water distribution networks in Tanzania. The selected district metering area (DMA) was found with a higher level of non-revenue water compared to that of the entire city water network. Despite the fact that the main drivers of high non-revenue physical water losses were attributed to high pressures in the system that caused leakages and pipe bursts; parts of the non-revenue water losses were also from the existing network topology. The simulation results showed that, pressure reduction strategies integrated with a change of network topology was able to efficiently lower the non-revenue water loss in the unplanned water network. This approach has shown to be an effective NRW reduction as compared to the common methods of pressure management alone and other tested scenarios. It was also found that optimization of pressure reducing valves was essential to effectively reducing the water losses in the network. Dividing the district metering area (DMA) into pressure sub-zones due to differences in demand patterns and elevations within the DMAs seemed to be appropriate management measure. Also, the sizes of pipe diameters higher than the required demand flows created low flow velocities within the distribution network and a rise in pressure heads. This study has shown the importance of combining temporal and spatial expansion of the distribution network with pressure management programs. Also, the topology of unplanned networks plays a big role in planning strategies for managing non-revenue water and improving urban water service delivery. It is essential to know the existing topology and hydraulic conditions of the system in order to predict the future performance of the city water infrastructures. The solution provided in this research includes best ways to cope with city growth regarding unplanned expansion of water distribution network which has been indicated as one of the contributors to high water loss. The saved water through reduction of persisted high NRW/ water loss would increase population accessing adequate and quality water supply and improve the water sustainability.

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.

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