Water Practice & Technology

Water Practice & Technology Vol 17 No 1, 14 doi: 10.2166/wpt.2021.124

Impact of active night population and leakage exponent on leakage estimation in developing countries

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ABSTRACT

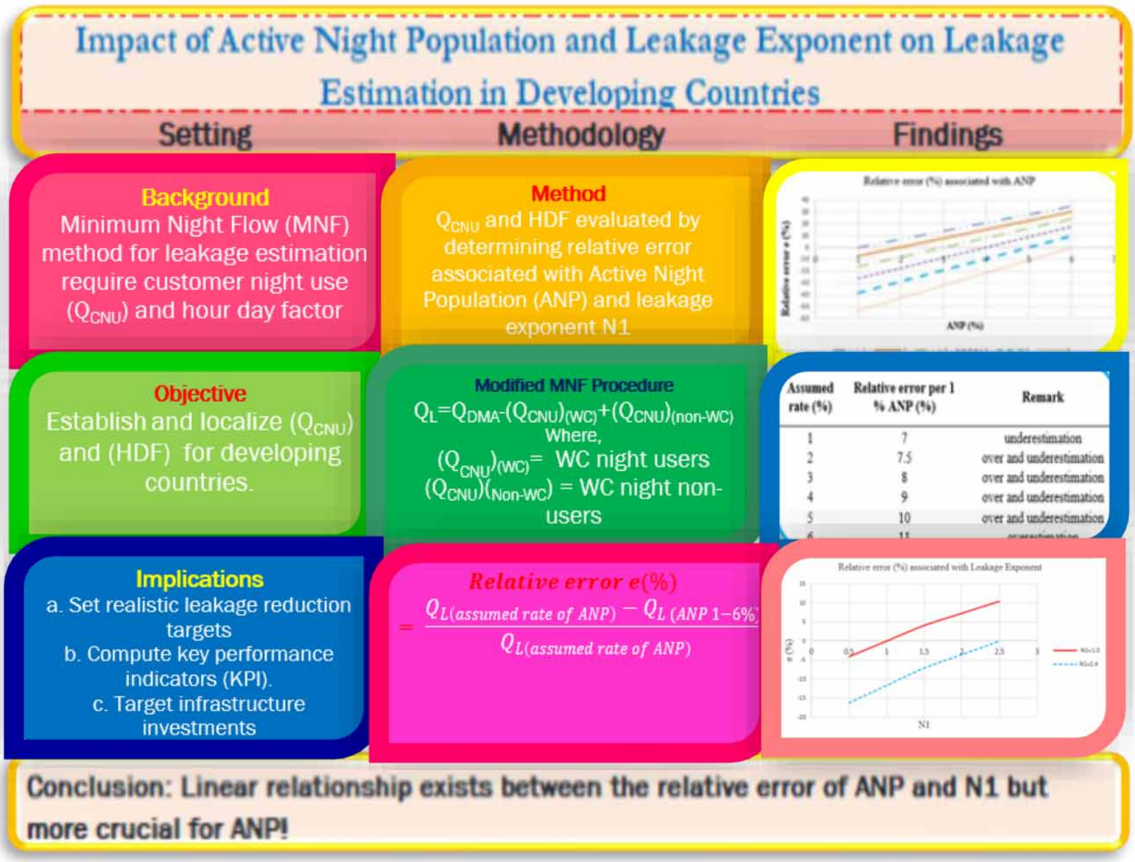
Methods for network leakage estimation include water balance, component analysis and minimum night flow (MNF) methods, the latter of which involves subtracting the customer night use (Q_{CNU}) from night leakage and multiplying by the hour day factor (HDF). Q_{CNU} and HDF respectively depend on Active Night Population (ANP) and leakage exponent (N1). In most developing countries, these parameters are assumed in the MNF method, thus introducing errors which makes setting realistic leakage reduction targets and key performance indicators (KPI) problematic. In this study, Q_{CNU} and HDF were evaluated by determining the relative error associated with ANP and N1 to establish localized rates for accurately estimating leakage in water networks. Between 7 and 11% relative error was associated with every 1% higher or lower ANP while up to 4% relative error was observed for every $N1$ step considered. A linear relationship exists between the relative error associated with both $N1$ and ANP although that of ANP is twice as high as $N1$. This has technical implications for setting water loss reduction targets and investing in the water infrastructure. It is recommended that water utilities must establish localized ANP and $N1$ values for accurate leakage estimation in water networks.

Key words: active night population, customer night use, hour-day factor, leakage exponent, performance indicators, relative error

HIGHLIGHTS

- Customer night use and Hour-day factor, which respectively depend on active night population and leakage exponent, are key parameters for use in the minimum night flow method.
- Active night population rate and leakage exponents will enhance the accuracy of the amount of leakage estimated.
- Key Performance indicators computed, realistic targets set and infrastructure investments for water loss reduction ensured.

GRAPHICAL ABSTRACT



1. INTRODUCTION

An estimated 666 million people lack improved drinking water worldwide (Ritchie & Roser 2019); amid the Sustainable Development Goals, SDG 6 aims at ensuring available and sustainable water for all by 2030. Van den Berg (2014) reports that huge volumes of treated water are physically and commercially lost from urban water supply systems annually as earlier reported by Kingdom *et al.* (2008). This loss amounts to 45 million cubic meters daily, costs the world approximately $5 billion a year, and is sufficient to serve nearly 200 million people worldwide (Kingdom *et al.* 2006).

Global leakage rates reported by Kingdom *et al.* (2006) have been corroborated by many other researchers. Burst losses and leaks contributed 13% out of 39% non-revenue water (NRW) in Sana, Yemen, 43% out of 51% NRW in Pirot, Serbia and 44% out of 50% NRW in Blantyre, Malawi (Kofodya 2010; Al-Washali *et al.* 2018; Radivojević *et al.* 2020). 67% in Selangor State, Malaysia. 59% in Kazerun, Iran, between 25 and 60% in five Bosnia-Herzegovinian utilities, 92% in Kafubu, Zambia and 44% in Kampala, Uganda (Chiipathenga 2008; Kamani *et al.* 2012; Vučijak *et al.* 2013). The reasons for these huge losses may be technical, socio-political and economic.

Studies by Knobloch *et al.* (2014) and Farley *et al.* (2011) indicate that the steps in addressing the leakage problem are fourfold; identify how much is lost, where the losses occur, why they occur and how they can be reduced. To determine how much is lost, three methods, namely – water balance (Farley *et al.* 2011; Knobloch *et al.* 2014), minimum night flow (MNF) (García *et al.* 2006; Tabesh *et al.* 2009; Xin *et al.* 2014) and component analysis also known as the Burst and Background Estimates (BABE) (McKenzie 2003; Fanner & Thornton 2005; Özdemir *et al.* 2021), have been identified and have been applied to the case study network in Amoatey *et al.* (2018).

The challenge these methods pose is their application to water networks with inadequate data, thus compelling water utilities to assume International Water Association (IWA) established parameters that may be sensitive to estimated leakage due to differing local conditions (Amoatey *et al.* 2018; Negharchi & Shafaghat 2020). For example, the infrastructure condition factor (ICF) and burst flow rates, used in the BABE method, must be determined per particular networks. However, in most developing countries, these factors have not been established, thus IWA rates, which are based on UK water networks, are used. Therefore, there is a need for water utilities in developing countries to develop local factors and rates for leakage estimation (Amoatey *et al.* 2018).

Similarly, the MNF method estimates leakage as the difference between night leakage (Q_L) and customer night use (Q_{CNU}), multiplied by the hour day factor (HDF). The active night population (ANP), is the percentage of customers that use water at night between 12:00 midnight and 04:00 am while the HDF accounts for the pressure variations during the day. The parameters, Q_{CNU} and HDF depend respectively on the ANP and the leakage exponent (N1). Q_{CNU} is also known as legitimate Night Consumption (LNC) and presupposes that customers with toilet flushing systems within a particular water distribution network, contribute to night flows. However, some people do not use toilet flushing systems which called for categorization of night users. These toilet-flusing and non-toilet flushing categories of night users is reported in earlier studies (Amoatey *et al.* 2014, 2018). The leakage exponent on the other hand depends on the pipe material, pipe age and environmental conditions of the network. As pipes of certain material advance in age, their response to changes in pressure varies and this can influence leakage exponent (Cheung *et al.* 2010; Lambert & Thornton 2012; De Marchis *et al.* 2016). Therefore, its influence in the estimation of leakage using the MNF method is being investigated in this study.

The influence of water loss (and NRW) parameters has been anticipated and have been the reason for various adaptations, modifications and re-definition of key concepts based on local network situations reported in previous studies (Tabesh & Asadiani Yekta (2005); Tsitsifli & Kanakoudis 2010; Al-Washali *et al.* 2020; Negharchi & Shafaghat 2020). Al-Washali *et al.* (2020) intimated that these have led to the introduction of correction factors, uncertainty, normalization, recognition of intermittent supply for among others.

It must be indicated that much has been reported on factors influencing apparent losses than have been reported on real losses. Fontanazza *et al.* (2015) identified meter age, meter inaccuracies, metering and billing errors incorrect installation practices, lack of maintenance or calibration, incorrect meter type and class and incorrect meter sizing as crucial for accurate estimation of apparent losses. The authors modeled the effect of private water tanks on apparent losses and recommended the use of unmeasured flow reducers (UFR) in such areas. Earlier authors like Tsitsifli & Kanakoudis (2010), Arregui *et al.* (2006), Tabesh & Asadiani Yekta (2005), Rizzo & Cilia (2005), Thornton & Rizzo (2002); have reported same.

With respect to real losses, though must has been studied on how to estimate the amount of leakage, not much has been explored as regards the influence of the factors used in these methods. Amoatey *et al.* (2018) identified the factors that influence all three leak estimation methods without analyzing the influence of the factors. The only study that has assessed the influence of some leak estimation parameters using the MNF method is that of García *et al.* (2006). The authors explored the influence of average zone pressure (AZP), the $N1$ and the MNF hour on the leakage level error and proposed guidelines to improve the assessment of daily leakage rates using the MNF method.

Amoatey *et al.* (2014, 2018) studies identifed Q_{CNU} to be crucial in the MNF procedure in developing country water networks and argues that, an assumption of the parameter may not depict the actual local situation and could lead to inaccurate estimation of losses, resulting in setting inaccurate water loss reduction targets. Negharchi & Shafaghat (2020) also investigated the influence of Q_{CNU} and N1 on the amount of leakage estimated using the BABE and MNF methods in a network where domestic customers use water tanks. The authors found that changing N1 by 0.1, alters the estimated leakage by 1%, while changing Q_{CNU} by one step, alters the calculated leakage by 14% although it is not clear what a step is in that study.

This study, therefore, seeks to investigate the influence of ANP and N1 on Q_{CNU} and HDF respectively and how both parameters subsequently influence estimated leakages. This is necessary since in the case study network, there are no automatic meter reading (AMR) systems that help identify typical night users and key water uses are not yet installed in the water network.

1.1. Active night population (ANP)

Farley (2001) recommends an ANP of 6% and this has been adopted in several studies (Fanner & Thornton 2005; Tabesh *et al.* 2009). ANP is the percentage of active consumers who use water between 12:00–4:00 am. The typical activities range are flushing of toilets, use of faucets, showers and use of washing machines is known as Q_{CNU} (Fantozzi & Lambert 2012). This parameter has been known to differ for different water networks and countries.

A summary of customer night use rates for different countries is documented in Amoatey *et al.* (2014) and updated by Negharchi & Shafaghat (2020).

Loureiro *et al.* (2012), identified social demographic factors such as property type, household size, daily habits of customers as well as technical, climatic factors and maintenance program of water utility as factors that influence Q_{CNU} and studied these extensively in Portugal. This makes the determination of ANP crucial for obtaining Q_{CNU}. Amoatey *et al.* (2018) identified three ways by which Q_{CNU} can be estimated but recommends using Automatic Meter Infrastructure (AMI) to identify the typical night uses and the active night population.

Fantozzi & Lambert (2012) carried out a study using smart metering systems in Australia and found ANP to be 3% confirming the fact that the recommendation to use 6% in earlier studies (Farley 2001; AL-Washali *et al.* 2019) might not be the same for all networks. This paper therefore posits that, some water networks especially in developing countries may have lower ANPs than the recommended 6% and the measured 3% (Fantozzi & Lambert 2012). Again, it is possible that with an increase in socio-economic activities coupled with the new way of working since the SARS-CoV 2 pandemic struck, ANP may be relatively higher in some networks than that found in the Fantozzi & Lambert (2012) study. Thus, it is imperative that water utilities know how far the leakage situation in the network is from reality. Since most developing country networks do not have AMI or smart metering systems, and not all consumers use toilet flushing systems, it is essential to investigate what relative error exists with the choice of an ANP rate.

1.2. Hour day factor

Another parameter under investigation is the *HDF* sometimes called night day factor (NDF) is a dimensionless parameter that presupposes that leakage and pressure are related, thus, by controlling pressure, water losses can be reduced (García *et al.* 2006; Cheung *et al.* 2010; Al-Washali *et al.* 2019; Özdemir *et al.* 2021). It is known from the Morrison *et al.* (2007) study that, gravity-fed networks and low-pressure gravity systems usually have *HDF* less than or equal to 24 hours per day due to high frictional head losses. *HDFs* depends on $N1$ and are estimated in the UK to range between 15 and 30, with an average of 22, and between 18 to 22 in South Africa (García *et al.* 2006; Cheung *et al.* 2010; Lambert & Thornton 2012). In a study in Kayseri, Turkey, Özdemir *et al.* (2021) found HDF to be 22.5.

Since $N1$ shows the interdependency of leakage on pressure, theoretically, leakage rates in water distribution systems vary with the square root of pressure (Lambert 2001; Cheung *et al.* 2010). Practically, however, tests in various countries have yielded higher N1 values due to changing flow conditions (laminar, transition or turbulent) and changing orifice area and size in terms of holes, slots or cracks of leaks (Lambert 2001). The determination of N1 is specific to any distribution network and is obtained from field studies by gradually reducing flow into a section of the network and recording changes in pressure over a period of time (Lambert 2001; Tabesh & Asadiani Yekta 2005; García *et al.* 2006; Thornton *et al.* 2008; Cheung *et al.* 2010). $N1$ values have been found to typically range from 0.5 to 2.5 (García *et al.* 2006; Tabesh *et al.* 2009; Cheung *et al.* 2010; Negharchi & Shafaghat 2020; Özdemir *et al.* 2021) depending on pipe material and level of leakage. The more rigid the pipe material, the closer the $N1$ is to 0.5. Networks with mixed materials range between 0.5 and 2.5. An established value of 1.15 is reported in Japan, 1.13 in UK distribution systems and close to 1.5 in Australia and New Zealand systems (Lambert 2001; Thornton & Lambert 2005; Lambert & Thornton 2012). Schwaller & van Zyl (2015) found N1 values between 0.46 and 1.67, with the vast majority of values lying between 0.5 and 1.5 in a model of the distribution of individual leaks and their parameters. It must be indicated therefore that the effect of age and material type of pipes has an indirect influence on $N1$ of the network (De Marchis *et al.* 2016).

This paper seeks to establish the influence of ANP in the Q_{CNU} and $N1$ in HDF parameters on the estimated leakage volume in developing country water networks. It emphasizes the need to establish these parameters for particular networks. The relative error associated with an assumed ANP and $N1$ is investigated to establish how changes in these parameters influence leakage volumes in a network. It is expected that water utilities in developing countries will adopt localized parameters to determine actual leakage levels so as to be able to accurately determine key performance indicators and set leakage reduction strategies.

2. MATERIALS AND METHODS

2.1. Case study area

The Baifikrom water network is located mainly in the Mfantsiman Municipal Assembly in the Central Region of Ghana and was selected as the study area for this work because the network had been zoned, expanded and rehabilitated. It supplies 32 communities with a population of about 122,000 (AVRL 2008), some of which are rural over an area of approximately 250 km^2. The design per capita consumption rates range from 30–75 litres/capita/day (Adombire 2007). The total demand is 318 m^3/h. Pipes are made of Asbestos Cement (AC), High Density Polyethylene (HDPE) and Polyvinyl Chloride (PVC) making about 150 km in length.

The pipe sizes range from 75–500 mm (AVRL 2008). The network (Figure 1) has approximately 5,700 service connections and 85% customer metering. Water is pumped from the Treatment Plant (WTP) into 4 reservoirs

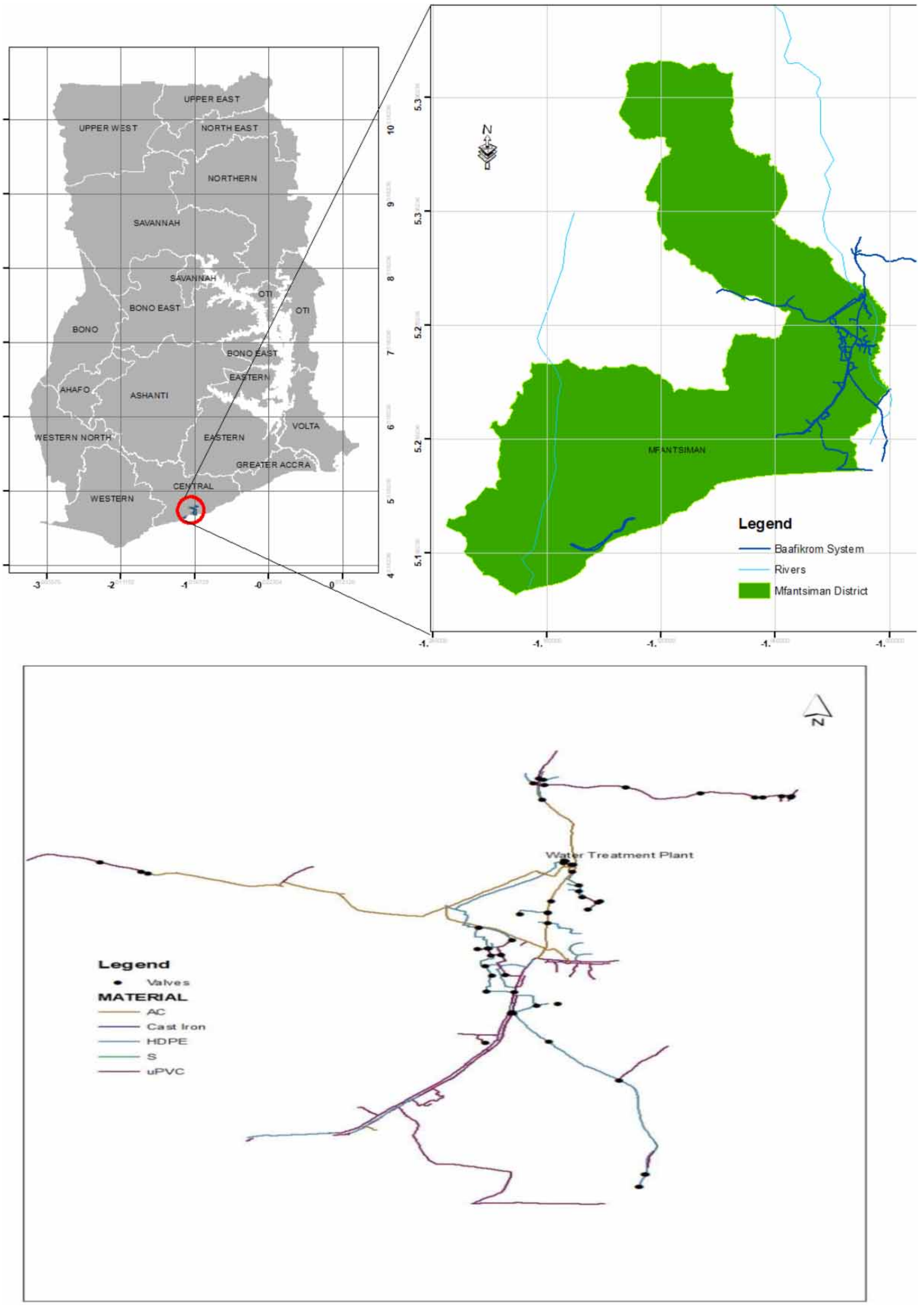


Figure 1 | Water distribution network for Baifikrom.

sited at the highest points (on hills) within the supply area. Water then flows under gravity from these reservoirs into the towns and communities. Rural communities are mainly served through public standpipes as some cannot afford a water meter connection. Also fixed outlet pressure reducing valves (PRVs) set at pressures between 10 and 30 m reduce flow to communities that branch off from the transmission mains.

Out of the 32 towns, 3 of them – Mankessim, Saltpond and Anomabo – are the most vibrant, with the remaining being rural farming and fishing communities. There is the market at Mankessim where vibrant commercial activities take place mainly during the day. It is the most populous town with a few commercial and rural banks. Saltpond and Anomabo have much smaller markets where fish, sea foods and salt are major commodities. There are a number of Secondary/High schools in these three towns. These towns are the most likely to have a section of their populace using toilet flushing systems. Most rural communities rely on public stand pipes and that accounts for the high number of stand pipes in this water network.

According to Mfantsiman Municipal Council (2012) assembly, only 10% of households use toilet flushing systems in this network. For this reason, the MNF procedure was modified to make it applicable to this network in an earlier study (Amoatey *et al.* 2018). The Baifikrom water network reports annual non-revenue water (NRW) of about 50% and this had not been broken down into its major components – leakage (physical) and apparent (commercial) losses (GWCL 2014). The NRW of the Baifikrom network is similar to other networks like Mwanza, Tanzania, Sana'a, Yemen and Zarqa, Jordan (Al-Washali *et al.* 2019).

After 3 months, the minimum night flow rate for the network was measured to be 40 m^3/h. N1 was found to be 2.4 resulting and an HDF of 20 obtained from pressure measurements taken over three weeks (Amoatey *et al.* 2012). Because the pipe materials in the case study network are 70% plastic, an $N1$ of 1.0 was theoretically expected (García *et al.* 2006; Lambert & Thornton 2012; De Marchis *et al.* 2016). In analyzing the relative error of leakage estimated for $N1$, for each ANP rate considered, a range of values 0.5 to 2.5 in steps of 0.5 is considered.

Q_{CNU} was estimated for two categories of night users and summed up in the same way as in the pilot study reported by Amoatey *et al.* (2014). Total Q_{CNU} was estimated for 1–6% ANP and used to estimate leakage. The relative error associated with each ANP rate was computed for $N1$, range of values based on the modified MNF method is assessed (Amoatey *et al.* 2014, 2018).

2.2. Method

2.2.1. Customer night use (Q_{CNU}) and leakage

García *et al.* (2006) determined uncertainties associated with the MNF reference hour and leakage exponent $N1$ on the estimated leakage using the relative error method. Negharchi & Shafaghat (2020) agree that some errors may be associated with the volume of leakage estimated due to initial assumptions and recommends that Q_{CNU} and N1 be established for network-specific uses. The method is used in this study to determine the error associated with assuming an ANP rate if the actual is lower or higher. In essence, how leakage is being under or overestimated if an assumed ANP is respectively lower or higher than the actual. The MNF procedure used in this study is described by Equations (2) and (3) (Amoatey *et al.* 2014, 2018) which is modified after Equation (1) (García *et al.* 2006; Cheung *et al.* 2010). The modification was necessary because most customers in the Baifikrom network do not use toilet flushing systems and therefore do not use the same amount of water during the minimum night period (12:00–4:00 am).

$$Q_L = Q_{DMA} - Q_{CNU} \tag{1}$$

where,

Q_L = leakage rate [m^3/h];
Q_{DMA} = flow rate into a District Metered Area [m^3/h]; and
Q_{CNU} = customer night use [m^3/h].

Q_L is the total leakage rate for the network, which is not evenly distributed during the day due to pressure variation. Q_L is therefore distributed throughout the day using the HDF (Equation (2)).

$$V_L = Q_L * HDF \tag{2}$$

where,

V_L = average daily leakage rate [m^3/h];
Q_L = leakage rate [m^3/h]; and
HDF = hour-day factor [-].

For each category, Q_{CNU} was computed by summing up the product of the assumed ANP by typical consumption volumes per typical night use (flushing toilets, washing of hands). The results and how it relates to similar studies have been discussed extensively in Amoatey *et al.* (2014). Therefore, the influence of ANP rate in Q_{CNU} and how it affects the amount of leakage cannot be overlooked.

$$Q_L = Q_{DMA} - (Q_{CNU_{WC}} + Q_{CNU_{Non-WC}}) \tag{3}$$

where,

$Q_{CNU_{WC}}$ = night use for customers who use WC [m^3/h];
$Q_{CNU_{Non-WC}}$ = night use for customers who do not use WC [m^3/h].

Just as ANP rates influence Q_{CNU}, HDF is also related to the N1 and is given by Equations (4) and (5). It shows how flow rates through existing leaks change from Q_0 to Q_1, as pressure changes from P_0 to P_1 at a rate of the leakage exponent N1 (Lambert 2001; Al-Washali *et al.* 2019). Thus, this study is also investigating how changes in N1 steps influence the amount of leakage.

$$\frac{Q_1}{Q_0} = \left(\frac{P_1}{P_0}\right)^{N1} \tag{4}$$

where,

Q_0 = flow rate in association with P_0 pressure;
Q_1 = flow rate in association with P_1 pressure; and
N_1 = leakage exponent.

$$HDF = \sum_{i=0}^{24}\left(\frac{P_i}{P_{\text{MNF hour}}}\right)^{N1} \tag{5}$$

where,

P_i is the average pressure in one observed point for each i time [m];
$P_{\text{MNF hour}}$ is the average pressure during minimum night hour [m]; and
$N1$ is the leakage exponent [–].

2.2.2. Relative error analysis

After estimating the amount of leakage for each ANP rate and each $N1$ step, relative to an assumed ANP rate and N1 step respectively, it was necessary to determine how incorrect a quantity is from a number considered to be true (Centre for Teaching & Learning 2015). It is estimated as the ratio of the difference between the amount of leakage estimated with a range of ANPs ($Q_{L\ (\text{ANP}_i)}$) and that estimated using an assumed rate of ANP to leakage estimated with an assumed ANP rate expressed in Equation (6) as follows (García *et al.* 2006; Centre for Teaching & Learning 2015):

$$\text{Relative error } e(\%) = \frac{Q_L(\text{assumed rate of ANP}) - Q_L\ (\text{ANP}_i)}{Q_L(\text{assumed rate of ANP})} \tag{6}$$

where,

$1\% \leq i \leq 6\%$;
$Q_{L(\text{assumed rate of ANP})}$ = leakage estimated at an assumed rate of ANP at each step; and
$Q_{L\ (\text{ANP } 1-6\%)}$ = leakage estimated at each ANP value.

This enables water utilities to see how much ANP and $N1$ contribute to the volume of leakage. Therefore, in this study, leakage was estimated for a 1–6% range of ANP and for each N1 step in the range, as indicated earlier. As indicated earlier, the range of ANP values considered, testing the uncertainty of in the range appears realistic for water networks around the world (Farley 2001; Fantozzi & Lambert 2012). The sensitivity of ANP for each $N1$ value in the range considered was determined by assuming a rate of 3%. The absolute error for the volume of leakage estimated determined for each ANP rate is compared with that of the assumed rate (Reuter & Liebsche 2008; Saltelli *et al.* 2008).

Ikonen (2016) proposed a one-factor-at-a-time (OAT) method, which determines the change in model output values that results from modest changes in model input values. However, since both ANP and $N1$ are necessary at the same time in the MNF method, both parameters interact to affect the precision of the amount of leakage estimated. In such a case, Loucks & Van Beek (2005) proposed a multivariate linear analysis to evaluate the approximate impact. This approach, however, requires a definition of the probability distributions of the parameter sets (N1 and ANP) which is difficult to establish in this study.

2.3. Limitations of the study

The challenge of finding other methods which could be confirmatory and more robust can be identified as a limitation of this study. The authors will consider some mathematical theorems and assumption that could explain such problems if the future. Many studies have been conducted on factors that influence accurate estimate of apparent losses (Thornton & Rizzo 2002; Tabesh & Asadiani Yekta 2005; Rizzo & Cilia 2005; Arregui *et al.* 2006; Tsitsifli & Kanakoudis 2010) but for real losses, only García *et al.* (2006) and Negharchi & Shafaghat (2020) have studied some leak estimation parameters, the later however, used actual measurements and no uncertainty analysis in particular.

3. RESULTS AND DISCUSSION

The results presented in Table 1 below have 3 parts as indicated by the solid lines, long dashes and short broken lines. The first part indicates the computation of Q_{CNU} per capita and for the entire population in the network for the two categories of night users – toilet flushing and non-toilet flushing customers. Following the procedure described earlier, Q_{CNU} for toilet flushing customers was found to range between 0.16 L/h and 0.71 L/h, whereas non-toilet flushing customers ranged between 0.03 L/h and 0.08 L/h respectively for ANP of 1%–6%. The per capita Q_{CNU} obtained was reported and discussed in Amoatey *et al.* (2014) study in comparison with similar rates from Uganda Mutikanga *et al.* (2010); and ASEAN region (Fantozzi & Lambert 2012).

The Q_{CNU} for the population per category was then computed and summed up, and the total Q_{CNU} for 3% ANP was found to be 9,845.4 L/h. Q_{CNU} estimates obtained were compared with a similar study in Kampala, Uganda and found to be realistic (Amoatey *et al.* 2014, 2018). These were subsequently used together with the measured night leakage and HDF to determine the leakage volume. The total daily leakage indicated by the region with long dashes was computed for each ANP over a range of five $N1$ with corresponding HDF values.

Leakage volume for Baifikrom network for $N1$ of 2.4 which translates into an HDF of 20 was found to be 663,401 L/day at 3% ANP (shown by the circled value). The third region (indicated by the short dashes), contains the percent leakage relative to the amount supplied for each $N1$ (with corresponding HDF) over 1–6% ANP. The percent leakage for each ANP for the expected theoretical $N1 = 1.0$ is between 9-14% and for the field-determined $N1 = 2.4$, leakage ranges between 8 and 13% of the supplied volume (see Table 1). Therefore, for an ANP of 3%, and $N1$ of 1.0, leakage is 12.4%, which indicates that leakage in the Baifikrom network is relatively lower in comparison with total leakage. The differences in leakage obtained per ANP rate reveal the importance of establishing actual rates for every network.

Considering that water loss for the entire study network is about 50%, the amount of leakage estimated appears to be small (Amoatey *et al.* 2018) even though similar in comparison with Al-Washali *et al.* (2019) findings for Zarqa (Jordan) and Mwanza (Tanzania) with average leakage of 15 and 11% respectively as against 66 and 46% NRW. It can therefore be seen that apparent losses are about three times higher than physical losses similar to other reports from Asia and Africa (Lievers & Barendregt 2009; Mutikanga *et al.* 2010).

Again, from Table 1, the relative error associated with the volume of leakage estimated for the range of ANP and N1 values using 3% and 1.5 as the nominal values respectively is indicated by the long dash double dot area. It can be seen that a 1% higher or lower ANP results in an 8% under-or overestimation of leakage. This implies that if AMR reveals that the actual ANP for the case study network is 2% instead of the 3% assumed nominal, the amount of leakage overestimated by 8% of the assumed nominal of 12%.

Although the Negharchi & Shafaghat (2020) did not investigate active night population in particular, the authors found that changing the measured legitimate night consumption (Q_{CNU}) by one step alters the calculated

Table 1 | Leakage estimation for Baifikrom water network

	Customer Category		1% ANP	2% ANP	3% ANP	4% ANP	5% ANP	6% ANP
Customer Night Use Estimates (L/h)	Q_{CNU} (WC) (L/person/h)		**0.16**	**0.27**	**0.38**	**0.49**	**0.60**	**0.71**
	Q_{CNU} (Non-WC) (L/person/h)		**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**
	$Q_{CNU\ (WC)pop}$ (L/h)		1,891.00	3,233.00	4,575.00	5,917.00	7,259.00	8,601.00
	$Q_{CNU\ (Non\text{-}WC)pop}$ (L/h)		3,074.40	4,172.40	5,270.40	6,368.40	7,466.40	8,564.40
	CNU total (L/h)		**4,965.40**	**7,405.40**	**9,845.40**	**12,285.40**	**14,725.40**	**17,165.40**
Total daily leakage Volume (L/day)	**N1**	**HDF**	**1% ANP**	**2% ANP**	**3% ANP**	**4% ANP**	**5% ANP**	**6% ANP**
	0.5	22.9	802,292	746,416	690,540	634,664	578,788	522,912
	1	22.0	770,761	717,081	663,401	609,721	556,041	502,361
	1.5	21.1	739,230	687,746	**636,262**	584,778	533,294	481,810
	2	20.4	714,706	664,930	615,154	565,378	515,602	465,826
	2.5	19.7	690,182	642,114	594,046	545,978	497,910	449,842
Leakage (%)	**N1**	**HDF**	**1% ANP**	**2% ANP**	**3% ANP**	**4% ANP**	**5% ANP**	**6% ANP**
	0.5	22.9	14.96	13.92	12.88	11.84	10.79	9.75
	1	22.0	14.37	13.37	**12.37**	11.37	10.37	9.37
	1.5	21.1	13.79	12.83	11.87	10.91	9.95	8.99
	2	20.4	13.33	12.40	11.47	10.54	9.62	8.69
	2.5	19.7	12.87	11.98	11.08	10.18	9.29	8.39
Relative error (%) with respect to QCNU (3% ANP)	**N1**	**HDF**	**1% ANP**	**2% ANP**	**3% ANP**	**4% ANP**	**5% ANP**	**6% ANP**
	0.5	22.9	-9.07	-7.60	0.00	7.60	15.19	22.79
	1	22.0	-9.07	-7.60	0.00	7.60	15.19	22.79
	1.5	21.1	-9.07	-7.60	0.00	7.60	15.19	22.79
	2	20.4	-9.07	-7.60	0.00	7.60	15.19	22.79
	2.5	19.7	-9.07	-7.60	0.00	7.60	15.19	22.79
Relative error (%) with respect to HDF (N1=1.5)	**N1**	**HDF**	**1% ANP**	**2% ANP**	**3% ANP**	**4% ANP**	**5% ANP**	**6% ANP**
	0.5	22.9	-8.53	-8.53	-8.53	-8.53	-8.53	-8.53
	1	22.0	-4.27	-4.27	-4.27	-4.27	-4.27	-4.27
	1.5	21.1	0.00	0.00	0.00	0.00	0.00	0.00
	2	20.4	3.32	3.32	3.32	3.32	3.32	3.32
	2.5	19.7	6.64	6.64	6.64	6.64	6.64	6.64

leakage by 14%. Again, because the authors were also interested in the influence of private water tanks on Q_{CNU}, the results were 14 times higher than the 1.7 litre/connection/hr recommended in the UK Water Industry (1994) report. In a summary of different customer night consumption values presented in Amoatey *et al.* (2014), it can be realized that studies in Ottawa, Canada, Malaysia were also higher than 1.7 lit/connection/hr. Again, though the premise of the Negharchi & Shafaghat (2020) study is not directly comparable with this study, it buttresses the fact that every water network is characteristic, and therefore cannot adapt parameters established elsewhere.

Similarly, the relative error associated with $N1$ of 1.5 as the nominal leakage exponent results in a maximum of 4% over or underestimation for a 0.5 lower or higher step respectively. It can be realized that there is an increasing linear relationship between a relative error of ANP and $N1$ irrespective of the assumed rate confirming the findings of García *et al.* (2006) for $N1$. With actual measurements, Negharchi & Shafaghat (2020) found that a 0.1 change in $N1$ results in a 1% change in leakage. Comparing the results of this study with the Negharchi & Shafaghat (2020) work, the results are similar, in that, since a linear relationship is linear relationship exist between $N1$, and leakage in this study, it can be inferred that a 0.1 step $N1$ results in a 0.8% leakage which is approximately 1%. The García *et al.* (2006) study however, reports a 10 times greater error for a $\pm 10\%$ change in $N1$ than $N1 = 1.0$ which is higher and probably more sensitive than this and the Negharchi & Shafaghat (2020) study. This supports the fact that networks differ and respond differently depending on the type of leak(s) predominant within the network.

With the arguments above, it can be seen that the accuracy of both parameters is crucial for quantifying leakage in water networks and this should be ensured by water utilities. Accurately estimating leakage has technical and research implications in that water utilities around the world are striving for efficiency in their services and in the management of the utility. In view of this, water utilities calculate key performance indicators (KPI) and set targets for leakage reduction and investment priorities. This makes the water utilities comparable with others around the world.

Again, since water loss is made up of leakage and apparent losses, the water utility can plan how to tackle apparent losses while it reduces leakage. For this reason, over or underestimating leakage further affects leakage reduction targets, and planning of maintenance investment priorities. Further research will consider a survey of ANP in the Baifikrom study network will be conducted to reduce leakage estimation uncertainties.

4. CONCLUSION

This paper investigated the relative error in leakage estimation using the minimum night flow method in the Baifikrom water network where some parameters have not yet been established and localized. Changes in the amount of leakage when a range of ANP rates for calculating Q_{CNU} and N1 values for estimating HDF was investigated. It was found that a linear relationship exists between the relative error of ANP and N1, although ANP is more crucial. It is recommended that water utilities must establish localized ANP and $N1$ values for accurate leakage estimation in water networks.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 8 June 2021; accepted in revised form 30 November 2021. Available online 13 December 2021