Leakage estimation in water networks based on two categories of night-time users: a case study of a developing country network
P. K. Amoatey, R. Minke and H. Steinmetz

ABSTRACT

The proportion of total water loss that is due to leakages and bursts in a district metered area in the Bafi krom supply network in the Central region of Ghana was investigated using the minimum night flow method. Legitimate customer night use was estimated specifically for the study area based on social habits, active population at night and demographic characteristics of two categories of night-time users identified – water closet users and ventilated improved pits users. It was estimated that 12% of the daily supply volume was lost through leakage indicating that apparent losses constitute 28%. This suggests that the water utility has to investigate the components of apparent losses and plan measures to reduce them in addition to reducing leakage.

Key words | active population, district metered area, hour-day factor, legitimate customer night use, minimum night flow, night-time users

INTRODUCTION

Real losses are leaks, bursts and overflows in water distribution systems. Apparent losses on the other hand, consist of losses resulting from water theft, data handling errors, meter under-registration and meter inaccuracies (see Table 1). Real and apparent losses make up water losses. Water loss was obtained by subtracting authorized consumption (legally used water) from the amount supplied to the network. This study is part of the research aimed at investigating measures to reduce losses in Ghana’s urban water supply network. The first step in this research is to determine the proportion of the total water loss which is physical leaks, bursts and overflows.

The average monthly volume of water supplied to the network and the average monthly amount of authorized water consumption records for 2010 and 2011 show that about 40% of the water supplied to the Bafi krom water distribution network is lost (Aqua Vitens Rand Limited (AVRL) 2011). Although, water loss in this case study is relatively lower than the national average of 50% (AVRL 2011), steps must be taken to reduce it since 40% of people living in urban areas do not have access to safe drinking water (Ghana Urban Water Limited (GUWL) 2012). The present losses of 40% in the study area can serve approximately 60,000 more people, at a rate of 75 L/day per person, which translates into more revenue for expansion and maintenance of the water network. Investigating the components of water losses is a must so as to strategically plan and implement water loss reduction activities.

Water utilities and researchers have been actively researching and tackling leakage management for over two decades. In the 1990s, the UK Leakage Control Initiative realized the need to develop a model that conceptualizes the individual components of physical losses. The method is known as BABE – Burst And Background Estimates – which identifies and estimates the physical losses as background losses, reported bursts and overflows, and unreported bursts and overflows in service reservoirs, transmission, distribution and customer supply lines (Lambert & Morrison 1996; McKenzie & Seago 2003).

Background losses are defined in the UK as the sum of all leaks with less than 0.5 m³/h flow rate, otherwise they are called bursts. Background losses can go undetected for a long...
time and constitute the bulk of physical or real losses. In 1994, the BABE methodology was improved to consider the effect of pressure on leakage (Lambert & Morrison 1996). This led to the introduction of a pressure correction factor, the Fixed And Variable Area Discharges concept, which indicates that the path of a leak could be ‘fixed’ or ‘variable’ depending on the pressure in the network (Lambert & Morrison 1996).

In 1999 the BENCHLEAK model was developed in South Africa based on the BABE concepts to estimate leakage and some performance indicators. Background losses were defined as leak events of 0.25 m³/h or less in the model (McKenzie 1999). Increasing knowledge in leakage management led to improvements in the later models like BENCHLOSS and BENCHLOSSNZ in Australia and New Zealand (McKenzie & Seago 2003). Others such as the LEAKS Suite (released in 2002), AQUALIBRE (released in 2004) and AQUALITE (released in 2007) among others were later developed (Liemberger & McKenzie 2006; McKenzie 2001; Tsitsifli & Kanakoudis 2009).

The minimum night flow (MNF) method is a practical approach to estimate all leaks and bursts in a water network. It is based on the fact that pressure in a water network is highest at the minimum night period (between 12:00 and 04:00 am). Since water consumption is low at that time, leakage forms a large proportion of night flows (Cheung et al. 2010; Deutsche Gesellschaft fuer Technische Zusammenarbeit (GTZ) 2010; United States Environmental Protection Agency (USEPA) 2010). Many water utilities have used the MNF method to identify problematic areas in sections of their water networks.

Mimi et al. (2004) used MNF analysis to trace leaks in zoned sections of the network and then used electro-acoustic techniques to pinpoint and repair leaks in Ramallah, Palestine. García et al. (2006) revisited the MNF methodology and assessed its sensitivity to factors like the reference hour and the average zone point. Rizzo et al. (2007) proposed the use of MNF to calculate total leakage in a network as an important step to investigate apparent losses.

Tabesh et al. (2009) developed an integrated model which combined MNF analysis with hydraulic simulation to evaluate losses in an Iranian water network while Cheung et al. (2010) introduced a calibration technique to calculate leakage by simulating pipe roughness and nodal emitter coefficients. Results were compared with that leakage estimated from MNF analysis in a network in south Brazil. According to Cheung et al. (2010) the calibration technique could be an alternative method for water utilities without supervisory control systems.

Finally, MNF analysis was carried out in a district metered area (DMA) as part of a water loss management research in Kampala. The results obtained were used together with the BABE concepts to quantify background losses (Mutikanga 2012). In all the above-mentioned studies, customer night use (CNU) was either measured, as in the case of Ramallah, or estimated, as in the case of the Iranian town, using active population at night.

To estimate leakage using the MNF method, legitimate CNU and hour-day factors (HDF) are needed (see Equations (3) and (4)). CNU is subtracted from the measured minimum night leakage rate (L/h) and the result is multiplied by HDF to convert leakage from an hourly rate to a daily volume. CNU is made up of three components: exceptional night uses, domestic and non-domestic night use (McKenzie 1999; García et al. 2006).
Exceptional night uses are measured and added to residential and non-residential night use (García et al. 2006). MNF for non-domestic uses can be logged using night flow analyzers with a high accuracy meter installed in series with the existing meter during the hours of 2:00 to 4:00 am at 30 min intervals for at least 7 days. A proportion of domestic users can be measured and projected to cover the population of domestic users (Mimi et al. 2004; Morrison et al. 2007).

Manual and fixed automatic meter readings during the MNF period is another way of gathering data to determine CNU (Thornton et al. 2008). Standard night factors from historical consumptions derived for various countries as suggested by Morrison et al. (2007) can be alternatively used to estimate household consumption rates. However, Farley (2001), Farley et al. (2008) recommends, multiplying the proportion of active residents who initiate a toilet flush during the MNF hour by the occupancy rate per household and average volume per toilet flush for a system with 100% metering.

Thornton et al. (2008) and McKenzie (1999) reported that 6% of population are active and initiate a toilet flush during the MNF period. However, a recent study using smart metering systems has shown that 3% of people are active during the MNF period. Other residential night uses observed include showers, washing machines, water from taps and leaky toilets (Fantozzi & Lambert 2012).

Customer legitimate night use rates for different countries compiled from previous studies (see Table 2) revealed a range of variability in CNU rates across the world. Countries like Malaysia and the USA are reported to have relatively high CNU rates of 5 L/property/h and 5.68 L/customer, respectively. These countries generally have relatively high per-capita water consumption rates. Malaysia, for instance is predominantly an Islamic nation and its high water rates could possibly be as a result of religious cleansing practices. Canada’s rate is 2.34 L/connection/h while in UK and South Africa it is 1.7 L/property/h. Countries like Germany and Austria use 0.4–0.8 L/person/h.

Therefore, CNU depends on the social habits, social status, demographic characteristics of an area, (property type, daily habits, and household size) type of technical installation, climatic or seasonal factors and maintenance program of the water utility (Loureiro et al. 2012). Adopting values from another country might not be a true reflection of the situation.

HDF is also known as hour-to-day factor, night day factor (Morrison et al. 2007; Cheung et al. 2010; Amoatey et al. 2012) or pressure correction factor (Farley et al. 2008). It is the factor which converts night leakage rate to daily leakage volume after CNU has been subtracted. Since pressure is not constant during the day, HDF accounts for pressure variations in a typical day (García et al. 2006; Morrison et al. 2007; Cheung et al. 2010).

If pressure were constant during the day, the HDF would be 24, which means there is no need for pressure management in the supply network. The lower the value than 24 hours per day, the more water can be saved through pressure reduction techniques (García et al. 2006). It is known from the Morrison et al. (2007) study that gravity-fed DMAs and low pressure gravity systems usually have a HDF less than or equal to 24 hours per day due to high frictional head losses. HDFs estimated in the UK range between 15 and 30, with an average of 22. In South Africa, they range from 18 to 22 (García 2006).

HDF can be calculated from leakage pressure measurements within the network and the exponent (N1). N1 is the rate at which leakage reduces when pressure is reduced. An N1 test was carried out by reducing pressure to the zone in 30-minute steps by throttling the valve during the minimum night hours (01:00–03:00 am). The pressures and flow rates were used to compute N1 as seen in Equation (1). Pressure measurements from different parts of the network were used to compute HDF (Equation (2)). HDF and N1 had been previously determined and found to be 19 and 2.4, respectively, which means that pressure management is essential for leakage reduction in the network. Detailed results and discussions can be found in Amoatey et al. (2012).

\[
\frac{Q_1}{Q_0} = \left(\frac{P_1}{P_0}\right)^{N1} \tag{1}
\]

where \(Q_0\) is the flow rate in association with \(P_0\) pressure, \(Q_1\) is the flow rate in association with \(P_1\) pressure, and \(N1\) is the leakage exponent.

\[
\text{HDF} = \sum_{t=0}^{24} \left(\frac{P_1}{P_{2-3}}\right)^{N1} \tag{2}
\]
where $P$ is the average pressure in one observed point of a DMA for each $i$ time, $P_{2,3}$ is the average pressure during minimum nightly consumption, and $N1$ is the orifice exponent.

### METHOD

The method used to estimate CNU and subsequently leakage is described.

#### Customer night use

Smart metering systems are not available in Ghana. A night flow analyzer for household night logging was also not available. CNU was estimated based on the nighttime activities observed in other smart metering systems. The factors considered were toilet flushing, the use of water faucets and showering. The active night population of 3% was adopted from the Fantozzi & Lambert (2012) study.

In this study, two categories of night-time users were identified – toilet flushing (water closet user) and non-toilet flushing (ventilated improved pit (VIP) user) groups. Per capita water consumption figures based on Ghanaian design standards for toilet flush, bathing and leaking faucets were obtained from Adombire (2007). The procedure used by Fantozzi & Lambert (2012) was followed to estimate CNU for the two groups of night users.

### Table 2 | Decision support system for legitimate night-time consumption (LNC)

<table>
<thead>
<tr>
<th>Country</th>
<th>Source</th>
<th>Factors considered</th>
<th>Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>General recommended</td>
<td>Managing leakage Report E Farley (2001)</td>
<td>Development of area, number of persons per km², social habits of the people</td>
<td>0.6 L/person/h</td>
</tr>
<tr>
<td>Canada (Ottawa)</td>
<td>Humaidi &amp; Brothers (2007)</td>
<td>Average volume of a toilet flush of 13 liters, average number of residents per connection of 3 and 6% of population active per hour</td>
<td>2.34 L/connection/h. Non-domestic demand 20 L/min (1,200 L/h)</td>
</tr>
<tr>
<td>Australia</td>
<td>Fantozzi &amp; Lambert (2012)</td>
<td>Toilet flushing and leaking faucets</td>
<td>1.08 L/connection/h</td>
</tr>
<tr>
<td>Germany (DVGW)</td>
<td>DVGW W 392 Fantozzi &amp; Lambert (2012), Liemberger (n.d)</td>
<td>2,000 to 40,000 people per district, no industrial night use</td>
<td>0.6 L/person/h</td>
</tr>
<tr>
<td>Austrian</td>
<td>Liemberger (n.d)</td>
<td>2,000 to 40,000 people per district, no industrial night use</td>
<td>0.4 to 0.8 L/person/h</td>
</tr>
<tr>
<td>Canada</td>
<td>Fantozzi &amp; Lambert (2012)</td>
<td>Not indicated</td>
<td>3 L/property/h</td>
</tr>
<tr>
<td>Malaysia</td>
<td>Fantozzi &amp; Lambert (2012)</td>
<td>Not indicated</td>
<td>5 L/property/h</td>
</tr>
<tr>
<td>Ramallah, Palestine</td>
<td>Mimi et al. (2004)</td>
<td>Development of area, number of persons per km², social habits of the people, and the season when the measurements are taken</td>
<td>0.2 and 0.5 L/s/km</td>
</tr>
<tr>
<td>South Africa</td>
<td>McKenzie (1999) (WRC, Report E)</td>
<td>6% of the population are active during MNF hour and water use in the order of 10 L/head/h based (toilet cistern)</td>
<td>1.7 L/household/h or 0.6 L/person/h</td>
</tr>
<tr>
<td>ASEAN Region</td>
<td>Fantozzi &amp; Lambert (2012)</td>
<td>3 occupants per property with 3% of active population using toilet, faucets and bath</td>
<td>0.45 L/person/h</td>
</tr>
<tr>
<td>Kampala, Uganda</td>
<td>Mutikanga (2012)</td>
<td>Logging at the minimum night period</td>
<td>1.4 L/residential property/h</td>
</tr>
</tbody>
</table>

*Customer, connection, residential property and household all imply that just ONE meter is billed.
Leakage estimation

Flow rates and pressure at the inlet to the DMA were logged at 15-minute intervals for 7 days in the Mankessim DMA (see Figure 1) to obtain the average MNF rate (see Figure 2). The MNF procedure to estimate leakage is explained in Equations (3) and (4) as reported in Cheung et al. (2014) and García et al. (2013).

\[ Q_L = Q_{DMA} - Q_{CNU} \]  

(3)

where \( Q_L \) is leakage rate also known as net night use, \( Q_{DMA} \) is flow rate into a district metered area, and \( Q_{CNU} \) is customer night use.

\[ V_L = Q_L \times HDF \]  

(4)

where \( V_L \) is average daily leakage rate in m³/day, \( Q_L \) is leakage rate in m³/hour, and HDF is the hour-day factor.

Case study

The method described was applied to the Mankessim DMA in the Baifikrom water network (see Figure 1). This DMA has a total network length of approximately 59 km and 2300 service connections with 85% customer metering. This DMA serves an estimated population of approximately 49,000 (AVRL 2008). The network was built first built in 1960 but was rehabilitated and expanded in 2008 (AVRL 2008).

Municipal sanitation records of the area as inferred from Ghana Districts (2012) indicates that only about 10% of the population use water closet (WC) toilet systems with the predominant facility being VIPs. This was the main social status and demographic factor which was considered in estimating CNU.

RESULTS AND DISCUSSION

Having followed the procedure described above, the estimated CNU is displayed (see Table 3). Estimated average night use per person for the toilet flushing and non-toilet flushing demand groups were 0.23 and 0.05 L/h respectively.

Customer night use

The computed CNU is relatively lower than those found in literature for different countries (see Table 2) due to the different prevailing social and demographic characteristics of the inhabitants in the area. Since the per capita water consumption for the communities in this case study is relatively
lower (ranging between 30 and 75 L/day), than the countries listed, it implies their economic and social status are lower than in many of the countries listed.

Although there was no household night logging, and there are no smart metering systems in the network, the comparison of CNU estimates with logged flows in Kampala, Uganda looks interesting. CNU per household was found to be 3 L/h, although household size was not indicated (Mutikanga 2012). An important clue however is that part of the population does not use toilet flush systems which brings the situation close to that of Mankessim DMA. Two scenarios in the Kampala study with respect to household type could be analyzed.

The first scenario could be a single family household of five people. In this case, CNU will be 0.6 L/person/h bringing the value close to CNU for Germany which appears too high in relation to the per capita consumption of the two countries and the fact that some households use pit latrines. The second scenario is the case where a household is made up of a number of families who share a single meter, with an average of say twelve persons per household, then, CNU will be 0.25 L/person/h which brings it close to the toilet flushing scenario of Ghana.

**Leakage estimation**

The 7-day pressure and flow readings are presented (see Figure 2). It was realized from the measurements that the MNF hour occurs between 01:00 and 04:00 am (see Figure 2). Flow rates and pressure were consistent for 5 out of the 7 days between 01:30 and 03:30 am. The average daily flow rate measured was 54,400 L/h (15.1 L/s) at an average pressure of 56 m and an average MNF rate of 11,900 L/h (02–03.04.2012 and 06–08.04.2012). Average flow for consistent days was 1,320 m³/day. A relatively higher average MNF rate of 50,000 L/h was observed for 2 consecutive days (04–05.04.2012, see Figure 2). Interestingly, the 2 observed abnormal days (04–05.04.2012, see Figure 2) were working days and therefore the anomaly is likely to be as a result of a burst.

The parameters used in estimating leakage are listed in Table 4. After subtracting the sum of CNU for the two categories of users, the result was multiplied by the HDF to obtain the total leakage for a day. Leakage estimated for the DMA was approximately 12% of the daily volume supplied (see Table 5). The estimated leakage appears relatively low for a network in a developing country like Ghana, however,

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**Table 3** Estimating customer night use (modified after Adombire 2007; Fantozzi & Lambert 2012; Ghana Districts 2012)

<table>
<thead>
<tr>
<th>Domestic</th>
<th>People-based night consumption</th>
<th>Average volume (L)</th>
<th>% of active population at MNF time</th>
<th>Average (L/person/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Customers with WC and bath/shower</td>
<td>Toilet flushing</td>
<td>5</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>Use of faucets</td>
<td>1.0</td>
<td>3</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Shower/bath</td>
<td>45</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Customers without WC</td>
<td>Toilet flushing</td>
<td>Not applicable</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Use of faucets</td>
<td>1.0</td>
<td>3</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Shower/bath</td>
<td>18</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td></td>
<td>0.05</td>
</tr>
</tbody>
</table>
it must be noted that CNU estimates are crucial for accurate leakage estimation. High CNU estimates will result in low leakage levels while low estimates will result in high leakage levels. The low leakage estimate could be as a result of the fact that one-third of the pipelines are relatively new. Reservoirs in the network are also relatively new. Three of the four reservoirs were built in 2008, while the capacity of the fourth one was doubled (AVRL 2008). Also, although maintenance is more reactive than proactive, the utility company responds to leaks and bursts within 48 hours as a matter of policy. Again, meter inaccuracies, illegal use and losses from public stand pipes have been found to constitute the bulk of apparent losses in developing countries. More so, it is reported that in Kampala (in Uganda) apparent losses constitute 52% of non-revenue water (NRW), while in Accra-Tema (in Ghana) they make up 55% of NRW (Mutikanga 2012).

The results give a signal that while the utility works towards finding ways to detect promptly and quickly repair leaks, a study should be undertaken to assess the Ghana Urban Water Limited’s customer database and the billing system. Public stand pipes should be monitored. Also meters should be monitored to ensure that they register actual consumption.

**CONCLUSION**

Customer night use was estimated for two categories of users in order to estimate total leakage in the Mankessim DMA. CNU for water closet users and VIP users was estimated to be 0.23 and 0.05 L/person/h respectively. It was found that 12% of the daily water supplied is lost through leakage (in effect, bursts and leaks). This implies that apparent losses constitute 28% of water losses in this network.

The results point to the fact that water utility operations should focus on measures to identify, locate and repair bursts and leaks promptly in order to reduce the physical losses but more importantly, they should investigate the components of apparent losses and tackle them.

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**Table 4 | Summary of parameters used in leakage estimation**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
<th>Value</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q(_{DMA})</td>
<td>DMA average flow rate</td>
<td>L/h</td>
<td>54,400</td>
<td>Obtained from MNF logging in Figure 2</td>
</tr>
<tr>
<td>Q(_{MNF})</td>
<td>DMA minimum night flow</td>
<td>L/h</td>
<td>11,900</td>
<td>Obtained from MNF logging in Figure 2</td>
</tr>
<tr>
<td>HDF</td>
<td>Hour-day factor</td>
<td>–</td>
<td>19</td>
<td>Previously determined from Amoatey et al. (2012)</td>
</tr>
<tr>
<td>(n)</td>
<td>No. of service connections</td>
<td>–</td>
<td>2,300</td>
<td>Provided by Water Utility</td>
</tr>
<tr>
<td>pop</td>
<td>Population (2010 est.)</td>
<td>–</td>
<td>49,000</td>
<td>Estimated from 2000 census data</td>
</tr>
<tr>
<td>(V(_{mon}))</td>
<td>Average system input</td>
<td>m(^3)/month</td>
<td>51,400</td>
<td>Provided by Water Utility for 2010 and 2011</td>
</tr>
<tr>
<td>(V(_{aut}))</td>
<td>Authorized consumption</td>
<td>m(^3)/month</td>
<td>30,000</td>
<td>Provided by Water Utility for 2010 and 2011</td>
</tr>
<tr>
<td>(V(_{day}))</td>
<td>Daily volume</td>
<td>m(^3)/day</td>
<td>1,320</td>
<td>Provided by Water Utility for 2010 and 2011</td>
</tr>
<tr>
<td>CNU(_{WC})</td>
<td>Customer night use (WC users)</td>
<td>L/person/h</td>
<td>0.23</td>
<td>Estimated in Table 3</td>
</tr>
<tr>
<td>CNU(_{NWC})</td>
<td>Customer night use (non-WC users)</td>
<td>L/person/h</td>
<td>0.05</td>
<td>Estimated in Table 3</td>
</tr>
<tr>
<td>CNU(_{total})</td>
<td>Total customer night use</td>
<td>L/h</td>
<td>3,330</td>
<td>Result computed in Table 5</td>
</tr>
<tr>
<td>(Q(_{L}))</td>
<td>Leakage rate</td>
<td>L/h</td>
<td>8,570</td>
<td>Result computed in Table 5</td>
</tr>
<tr>
<td>(V(_{L}))</td>
<td>Leakage volume</td>
<td>m(^3)/day</td>
<td>163</td>
<td>Result computed in Table 5</td>
</tr>
<tr>
<td>(T(_{L}))</td>
<td>Total leakage</td>
<td>%</td>
<td>12</td>
<td>Result computed in Table 5</td>
</tr>
</tbody>
</table>

Assumptions: Non-property leakage is included in estimated night use per hour 10% of population use WC based on sanitation records for Mfantsiman Municipality (Ghana Districts 2012).

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**Table 5 | Summary of leakage analysis for Mankessim DMA**

<table>
<thead>
<tr>
<th>(CNU(<em>{WC})(</em>{total})) (L/h)</th>
<th>(CNU(<em>{NWC})(</em>{total})) (L/h)</th>
<th>(CNU(_{total})) (L/h)</th>
<th>(Q(_{L})) (L/h)</th>
<th>(V(_{L})) (m(^3)/day)</th>
<th>(T(_{L})) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 * pop * CNU(_{WC})</td>
<td>0.9 * pop * CNU(_{NWC})</td>
<td>CNU(<em>{WC})(</em>{total}) + CNU(<em>{NWC})(</em>{total})</td>
<td>8,570</td>
<td>163</td>
<td>12</td>
</tr>
<tr>
<td>1,130</td>
<td>2,210</td>
<td>3,330</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Table 4 | Summary of parameters used in leakage estimation

Table 5 | Summary of leakage analysis for Mankessim DMA
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