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Methods, applications, uncertainties, and implications in intermittent supply

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Review

Assessment of water losses in distribution networks: Methods, applications, uncertainties, and implications in intermittent supply

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ABSTRACT

Reducing all water loss components to zero is neither technically possible nor economically viable. The water loss components should be accurately assessed and prioritised for a reduction. This paper investigates all methods that break down the water losses in distribution networks into apparent and real losses. Their accuracies and uncertainties are discussed and applications to three case studies in developing countries are presented. The results show that different methods estimate the water loss components differently. Consequently, different reduction measures are planned and prioritised. Interestingly, the least accurate methods have a low level of uncertainty, but more realistic assumptions yield higher uncertainties. This suggests that the uncertainty analysis only assists in improving the outputs of each of the methods but does not demonstrate their accuracy. The cost of water loss varies depending on the used assessment method and the economic feasibility of the reduction measures is significantly influenced. The water loss components should therefore be assessed for the whole network using at least two methods to reasonably model and monitor the loss reduction in water distribution networks.

1. Introduction

The access to water is crucial for life, prosperity, and all human activities (Dighade et al., 2014). Water resources must be used effectively to meet the demand of the ever-growing population, considering the limited and dwindling water availability (Connor et al., 2017). However, supplying safe water while preserving water resources is a difficult task because a significant portion of the supplied water does not reach its intended users but is lost on the way as leakage or is stolen from the distribution networks. The major amount of leakage is avoidable; however, a certain portion of leakage is unavoidable, even in new and well-managed water distribution networks (Lambert et al., 1999, 2014). Leakage keeps increasing unless it is controlled. Reducing the leakage is like walking down a rising escalator; it should be faster and more effective than the natural rise of leakage (European Commission, 2015; Lambert and Fantozzi, 2005; Lambert and Lalonde, 2005). The annual water loss (WL) volume worldwide is substantial; it has been estimated to be 126 billion cubic metres, which costs about 39 billion USD annually (Liemberger and Wyatt, 2018). The WL is either leakage or real loss (RL) occurring in pipes, storage reservoirs, and customer connections or apparent loss (AL) occurring due to customer meter underregistration, errors in data handling and billing, or unauthorised use (Lambert and Hirner, 2000). The sum of the volume of WL and the volume of unbilled authorised consumption (UAC), which is the authorised use that has no revenue, such as water used for firefighting or network cleaning, is called non-revenue water (NRW). The WL causes water waste, the technical instability of the network components, water quality deterioration, inequities in the water distribution, increasing operation and maintenance costs, and loss of revenues that are necessary for sustaining and expanding the access to water.

Reducing all WL components to zero is neither technically possible (Lambert et al., 2014) nor economically feasible because the greater the level of the resources employed is, the lower are the additional marginal benefits (Ashton and Hope, 2001; Kanakoudis et al., 2012; Pearson and Trow, 2005). After a certain WL level, that is, the economic level of WL, any further investment does not result in cost-effective water savings, excluding the environmental costs and impacts of water abstraction (Ashton and Hope, 2001; Molinos-Senante et al., 2016). To

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Nomenclature

α	exfiltration–infiltration factor
β	unbilled authorised consumption factor
γ	outdoor water use factor
$\delta U/\delta$	partial derivative of the variable U with respect to an independent parameter
ΔA	uncertainties of the variable A
AL	apparent loss (or commercial loss)
ALC	active leakage control using leak detection surveys
BABE	bursts and background estimates methodology
BC	billed consumption
BMC	billed metered consumption
BUC	billed unmetered consumption
CI	intervention cost
CMIs	customer meter inaccuracies
CHK_1	logical check = $M_{1b} - M_4 = M_3$
CV	variable cost
DHEs	data handling errors
DMA	district metered area
EIF	economic intervention frequency based on the leakage detection surveys
EP	economic percentage of systems to be surveyed annually
M_{1a}	top-down water balance assuming the unauthorised consumption to be 0.25% of the SIV
M_{1b}	top-down water balance assuming the unauthorised consumption to be 10% of the BC
M_2	water and wastewater balance method
M_3	MNF analysis method
M_4	BABE method
MNF	minimum night flow
N_1	leakage exponent
N_p	population with wastewater service
NDF	night–day factor
NRW	non-revenue water
PM	pressure management
P_{min}	average pressure during the minimum night hour
P_i	average pressure during the hours of the day
q_{cap}	per capita water consumption
$q_{bc.min.mon}$	volume of the billed consumption in the minimum month of the year
Q_{AL}	apparent losses (m^3/yr)
Q_{bc}	billed consumption (m^3/yr)
Q_{ex}	volume of exfiltration (m^3/yr)
Q_{ind}	industrial and commercial wastewater discharge
Q_{inf}	volume of infiltration/inflow (m^3/yr)
Q_{LNF}	legitimate night flow (m^3/h)
Q_{MNF}	minimum night flow (m^3/h)
Q_{NNF}	net night flow (m^3/h)
Q_{RL}	daily rate of the real losses in the DMA (m^3/h)
Q_{ss}	supplementary supply through water tankers
Q_{ww}	inflow to the WWTP (m^3/yr)
RL	real losses (or leakage)
RR	rate of rise of the unreported leakage (m^3/km mains/d/yr)
RT	response time to repair leaks
SIV	system input volume
UAC	unbilled authorised consumption
UC	unauthorised consumption
UMC	unbilled metered authorised consumption
WL	water loss
UUC	unbilled unmetered authorised consumption

effectively and efficiently minimise the WL, the WL should be diagnosed, its components and subcomponents should be assessed, and their reduction should be prioritised (Kanakoudis and Tsitsifli, 2014; Mutikanga et al., 2012; Puust et al., 2010). However, thorough methods for WL assessment were not available two decades ago (Liemberger and Farley, 2004). Later, significant advancements were made due to the development of new concepts and methods for WL management (Mutikanga, 2012; Vermersch and Rizzo, 2008). The components of WL (RL and AL) can be assessed using the common top-down water audit methodology (AWWA, 2016; Lambert and Hirner, 2000) or, alternatively, by establishing a water and wastewater balance (AL-Washali et al., 2018). Leakage can also be estimated using Minimum Night Flow (MNF) analysis (Eugine, 2017; Farah and Shahrour, 2017; Farley and Trow, 2003; Puust et al., 2010) or the component analysis of the leakage (AL-Washali et al., 2016; AWWA, 2016; Lambert, 1994). Yet, these methods use different approaches (and scales) to estimate the WL components and thus different corrective measures are prioritised (AL-Washali et al., 2019b) and different economic levels of leakage are planned, contributing to less effective WL management. A detailed review of three methods of water loss component assessment is presented in the literature (AL-Washali et al., 2016). This paper, however, reviews briefly and investigates four methods, developments, applications and uncertainties of WL component assessment using three case studies in developing countries: Zarqa, Jordan; Sana'a, Yemen; and Mwanza, Tanzania. Subsequently, the sensitivity of the WL component assessment for planning WL reduction and interventions, particularly leakage reduction, is analysed. The results can be used to enhance the accuracy of WL component assessments and facilitate more reasonable planning and more effective WL management in water distribution networks, especially with respect to intermittent supplies and developing countries.

2. Water loss component assessment methods

The magnitudes of WL components (RL and AL) can be analysed using four methods. Table 1 summarises these methods and their approaches, which are further discussed in the following paragraphs.

2.1. Top-down water balance

In this method, first, the AL components are estimated and the RL volume is then calculated from the volume of WL. After determining the system input volume and billed consumption (BC), the NRW volume can be calculated using Eq. (1). The WL volume is then calculated by subtracting the UAC from the NRW volume [Eq. (2)]. The AL is then estimated by investigating and/or assuming its subcomponents, that is, the meter inaccuracies, data handling errors, and unauthorised consumption (UC). The customer meter inaccuracies should be estimated according to meter tests at different flow rates, representing typical customer water use and meter guidance manuals (Arregui et al., 2007; AWWA, 2016). The data handling errors can be estimated by exporting and analysing historic billing data trends for a certain period (Farley et al., 2008; Mutikanga et al., 2011). The unauthorised use should be estimated via the utility's experience with validated data. However, estimating the individual components of the UC is a tedious task that requires time and resources (AWWA, 2009). Therefore, assuming the UC volume is a common practice. The UC is assumed to be 0.1% of the supplied water (Lambert and Taylor, 2010; Vermersch et al., 2016) or 0.25% of the supplied water, as recommended by the AWWA (2009). For developing countries, it is suggested to assume it as 10% of the billed water or 10% of NRW as proposed by Mutikanga et al. (2011) and Seago et al. (2004). Although these assumptions are closer to actual cases in developing countries, they represent nothing but speculations that are not very useful for monitoring the UC or improving the RL

Table 1
Methods for water loss component assessment.

Method	Reference	Scale	Approach	Limitations
Top-down water audit	Lambert and Hirner, 2000	system-wide	- assume and estimate AL components and then calculate RL - desk method - pressure-independent - cost-effective	- focus on RL not AL - generic assumptions of AL - no methodology to estimate unauthorized consumption - likely overestimates RL
Water and wastewater balance	AL-Washali et al., 2018	system-wide	- estimate AL using WWTP inflow measurements and then calculate RL - desk method - pressure-independent - cost-effective	- requires centralised sewers for all or part of the network. - needs measurements of WWTP inflows
MNF analysis	Farley and Trow, 2003	District Metered Area (DMA) scale	- estimate leakage in a part of the network - both assessment and reduction process - actual measurements - pressure-dependent	- intensive field work, zoning - requires trained manpower and sophisticated equipment - estimates leakage in a part of the network during a time of the year
Component analysis of leakage (BABE)	Lambert, 1994	system-wide	- analyse field data and volumes of bursts and the rates of small background leaks - the only method that breaks down RL into subcomponents, cost effective - clarifies the nature of leakage and simulates its reduction - pressure-dependent	- many assumptions - applicable only for utilities that have regular active leakage control (ALC) - underestimates RL - further calibrations are useful

estimation in developing countries (AL-Washali et al., 2016, 2018). After the subcomponents of the AL are estimated and aggregated, the RL volume can be calculated using Eq. (2). Subsequently, the international water association (IWA) standard water balance can be established. Based on this balance, the best-practice WL performance indicators can be calculated for WL target monitoring and leakage benchmarking (Alegre et al., 2016, 2000; Lambert and Hirner, 2000). In addition, normalising the WL performance indicators is therefore necessary for setting targets and benchmarking (AL-Washali et al., 2019a; Frauendorfer and Liemberger, 2010):

$$NRW = SIV - BC \tag{1}$$

$$WL = NRW - UAC = AL + RL \tag{2}$$

where NRW is the non-revenue water (m^3/year), SIV is the system input volume (m^3/year), BC is the billed consumption, WL is the WL volume (m^3/year), UAC is the unbilled authorised consumption (m^3/year), AL is the apparent loss, and RL is the real loss.

2.2. Water and wastewater balance method

AL-Washali et al. (2018) suggested an approach for the assessment of the NRW components by using the Apparent Loss Estimation (ALE) equation [Eq. (3)]. The AL is estimated by establishing a water–-wastewater mass balance, where it is assumed that the actual water consumed by the users eventually enters the sewers and reaches the wastewater treatment plant (WWTP). In contrast to the billing system and BC, the flows in the sewers are not affected or reduced by customer meter inaccuracies or data handling errors. The sewer flow represents the actual consumption including the consumption through illegal connections and bypasses. Hence, the AL volume can be determined by analysing the WWTP inflow and the RL can be calculated. The ALE equation [Eq. (3)] is used to estimate the AL with this method (AL-Washali et al., 2018):

$$Q_{AL} = (\alpha + 1)Q_{ww} - (\beta - \gamma + 1)Q_{bc} \tag{3}$$

where Q_{AL} is the apparent loss (m^3/year) if the assessment period is one year; Q_{ww} is the inflow to the WWTP (m^3/year); Q_{bc} is the billed consumption (m^3/year); α, β, and γ are case-specific factors; α is the exfiltration–infiltration factor (3%–10%), β is the unbilled authorised consumption factor (0.5%–1.5%); and γ is the outdoor water use factor (4%–40%).

The factors α, β, and γ should be estimated, assumed or optimised first; subsequently, the ALE equation can be used to estimate the AL quantity. The sensitivities and uncertainties of these factors are analysed in AL-Washali et al. (2018). Factor α can be assumed and then verified using Eq. (4) based on which the exfiltration and infiltration to the sewers can be calculated using the billing data and measured per capita consumption:

$$\alpha = Q_{ex} - Q_{inf} = N_p \times q_{cap}(1 - \gamma \div 100) + Q_{ind} - Q_{ww} \tag{4}$$

where Q_{ex} is the exfiltration volume, Q_{inf} is the infiltration/inflow volume, N_p is the population with wastewater service, q_{cap} is the per capita water consumption, γ is the outdoor use percentage of the water consumption, Q_{ind} is the industrial and commercial wastewater discharge, and Q_{ww} is the WWTP inflow.

The UAC volume (e.g. firefighting, pipe flushing), that is, factor β, can be estimated based on water utility data or using 0.5% of the billed water or 1.25% of the SIV. The volume of the outdoor water use, factor γ, can be calculated using Eq. (5) and monthly billing data:

$$\gamma = \frac{Q_{bc} - 12 \times q_{bc.min.month}}{Q_{bc}} \times 100 \tag{5}$$

where γ is the outdoor water use percentage, Q_{bc} is the annual volume of the BC, and $q_{bc.min.month}$ is the volume of the BC in the minimum consumption month of the year.

Finally, to apply this method, the volumes of the two main variables Q_{ww} and Q_{bc} should be adjusted to represent only customers with water and wastewater services, that is, excluding those with only water or only wastewater services as explained in AL-Washali et al. (2018). The volume of the WWTP inflow should exclude the volumes of rainy days throughout the year and should be substituted by the average dry weather inflow. The AL rate per customer can then be calculated using the ALE equation and can be generalised for all water customers. Subsequently, the RL volume can be calculated from the total WL volume. One limitation of this method is the need of good WWTP inflow measurements. In addition, it can only be applied when a centralised sewer system is available for parts of or all customers. The sewer networks are also not available for many cities in developing countries as they require bigger funds and resources than water supply networks.

2.3. Minimum night flow (MNF) analysis

Based on MNF analysis, the RL can be analysed in one or several small and separated areas within the network. The AL can then be calculated from the WL volume. After a district metered area (DMA) is established (Deuerlein, 2008; Farley and Trow, 2003; Galdiero et al., 2015; Kesavan and Chandrashekar, 1972; Morrison et al., 2007), a flow meter and data logger are installed at the inlet of the DMA. Several pressure gauges and data loggers are usually installed at several points in the DMA to determine the pressures in the DMA. The MNF is the lowest flow in the DMA over the whole 24 h of the day, which usually occurs between 02:00 and 04:00 am when most of the customers are usually inactive; the flow at this time is mainly leakage (Liemberger and Farley, 2004; Puust et al., 2010). However, the situation differs for intermittent supplies; the DMA should be supplied with water until all customers are saturated and the elevated and ground tanks in the network are completely full (AL-Washali et al., 2019b). In this case, the MNF can occur at any time during the day but is anticipated in the early morning, depending on the water use, whether it is directly from the tank or through pumping to another elevated tank, as the system becomes continuous during the experiment. The leaks during the MNF hour are then estimated after subtracting the possible legitimate night consumption in the DMA using Eq. (6) (Farley and Trow, 2003; Hamilton and McKenzie, 2014). However, Eq. (6) represents the leakage rate of the MNF hour, which is higher than the leakage rate during the other hours of the day, mainly because of the pressure–leakage relationship (Lambert, 2019; Van Zyl and Cassa, 2014; Van Zyl et al., 2017). To obtain the rate of the real losses during the day, the leakage rate is adjusted using a pressure correction called night–day factor (NDF), which can be calculated using Eq. (7) (Lambert et al., 2017; Morrison et al., 2007). The pressures in the NDF should include the pressure during the whole day and represent the normal actual situation in the DMA. Subsequently, the RL rate can be calculated using Eq. (8) and the AL can then be obtained from the WL volume:

$$Q_{NNF} = Q_{MNF} - Q_{LNF} \tag{6}$$

$$NDF = \sum_{i=0}^{23} \left(\frac{P_i}{P_{min}}\right)^{N_1} \tag{7}$$

$$Q_{RL} = Q_{NNF} \times NDF \tag{8}$$

where Q_{NNF} is the net night flow (m^3/h), Q_{MNF} is the minimum night flow (m^3/h), Q_{LNF} is the legitimate night flow (m^3/h), NDF is the night–day factor, P_{min} is the average pressure during the minimum night hour, P_i is the average pressure during the day hours, N_1 is the leakage exponent that can be assumed to be 1 (May, 1994; McKenzie, 2003; Morrison et al., 2007), and Q_{RL} is the daily rate of the RL in the DMA (m^3/h).

This method is limited to applications in DMAs and cannot be generalised for the entire system or the whole year, unless there are abundant field data and DMAs and the measurements are obtained throughout the year. In all cases, this method is 'data-hungry' and less cost-effective than other methods.

2.4. Component analysis of the leakage

The component analysis of the leakage, also known as the Burst and Background Estimates (BABE), is originally an empirical model. Based on the BABE concept, a certain part of the RL is analysed (Lambert, 1994). This method is more frequently used for the analysis of RL 'subcomponents' than as a WL component assessment method. Based on this method, the RL consist of numerous leakage events, where the loss volume of each event is a function of the flow rate and average runtime for different types of leakages. The volume of an individual leak or burst is calculated as the average flow rate multiplied by the duration of the leak or burst. Based on this concept, part of the leakage is avoidable and the rest is unavoidable. The avoidable leakage can be calculated using the factors presented in Table 6.1 in Farley et al. (2008), at a pressure of 50 m or in Lambert et al. (1999). The unavoidable leakage can be estimated using Eq. (9) or, alternatively, using the factors presented in Table 2 in Lambert (2009). A correction factor called Infrastructure Condition Factor (ICF = 1–3) is then applied to the unavoidable background leakage to consider the differences between the conditions of cases for which this model is developed to other cases, as discussed in Fanner and Thornton (2005):

$$UL = \left(18\frac{L_m}{N_c} + 0.80 + 0.025L_P\right)P_{avg} \tag{9}$$

where UL is the unavoidable leakage volume (L/service connection · day), L_m is the length of the mains (km), N_c is the number of service connections, L_P is the total length of the house connection between the edge of the street and customer meter, and P_{avg} is the average operating pressure of the network (m).

Note that this method is unique because it is the only way to break down real losses into subcomponents, understand the nature of the leakage, and plan its reduction in a case-specific manner. However, many assumptions of the model do not fit other distribution systems such as the leakage detection policy and the quality of the construction and pipe materials. This method is therefore susceptible to a significant underestimation of the leakage volume.

3. Application of the methods

3.1. Description of the case study systems

3.1.1. Zarqa, Jordan

The Zarqa water supply system serves 160,000 customers, with an average of 6.3 people per customer, that is, ~1 million users. The water source is a quantity allocated from the Disi water project, accounting for 43% of the water supply, and the water abstracted from 99 wells (57% of the water supply). The length of the mains in the network is 2447 km according to available GIS data. The supply network of Zarqa is constructed of polyethylene, iron pipes (galvanised, ductile, and cast), and steel pipes. The system is an almost fully pumped system apart from small parts of the network, which are supplied either by gravity or the combination of pumping and gravity. The network can be divided into two main zones based on the operation: 1) Rusaifah directorate; and 2) Zarqa directorate, which is responsible for the whole network, except for the Rusaifah zone. The Zarqa directorate is further subdivided into five interlinked and multi-fed subzones. The supply pattern in the Zarqa network is intermittent with an average supply of 36 h per week. The average NRW level for the period of 2006–2015 was 29.2 million cubic metre (MCM), accounting for 57% of the system input volume (AL-Washali et al., 2019b).

3.1.2. Sana'a, Yemen

The Sana'a water supply system serves 94,723 customers, with 16 people per customer, that is, ~1.5 million users. The only water source consists of 114 deep wells with depths reaching 1000 m below ground. The length of the network mains is 977 km according to available GIS data. The mains are constructed of ductile iron, unplasticised polyvinyl chloride, and asbestos-cement pipes with diameters ranging from 150 to 800 mm. The submains and service connections are constructed from galvanised iron and high-density polyethylene. The water supply in Sana'a is a combined system including both pumped and gravity supplies. Approximately 50% of the network is mainly pumped from the headworks. The supply network can be geographically divided into six administrative zones and 369 interlinked and multi-fed distribution areas. The Sana'a water supply is intermittent and insufficient. Typically, a customer receives water once a week, with an average supply time of 4.4 h/d. If the supplied water is insufficient, customers buy additional water from private water tankers (AL-Washali et al., 2018). Based on obtained field data, the average NRW level in Sana'a for the period of 2005–2015 was 7.1 MCM, accounting for 35% of the system input volume.

3.1.3. Mwanza, Tanzania

The Mwanza water supply system serves 49,284 customers (as in 2015), with 15.5 people per customer, that is, ~0.77 million users. The main source of water is raw water from Lake Victoria with an elevation difference of 74 m. The length of the network mains is 870 km. The submains are constructed from ductile and cast iron, polyvinyl chloride, high-density polyethylene, and polyethylene pipes with diameters ranging from 25 to 500 mm. The water in Mwanza is almost continuous pumped supply, with an average supply time of 22 h/d. The supply network can be divided into five zones and several separated DMAs among which few contain flow meters to measure the inflow to these areas. Based on obtained field data, the average NRW level in Mwanza for the period of 2009–2015 was 14.3 MCM, accounting for 48% of the system input volume.

3.2. Application of the methods

3.2.1. Water balance

The top-down water balance method was applied in the three case studies. For the Zarqa water supply system, the customer meter inaccuracies were estimated by Zarqa water utility based on a lab bench test for a sample of customer meters for different float-valve flows of the tanks. The data handling errors were estimated by extensive audits of the billing data of the water utility conducted by the authors. On the other hand, two assumptions were made regarding the UC, that is, 0.25% of the system input volume (AWWA, 2009) and 10% of the billed water (Mutikanga et al., 2011), which is close to other recommendations for developing countries (Seago et al., 2004; Wyatt, 2010). Based on these two assumptions, two different AL volumes were estimated; accordingly, two different RL volumes were calculated from the WL volume.

Similarly, the customer meter inaccuracies for the Sana'a water supply system were estimated by the authors based on a lab bench test on 22 customer meters representing different types, ages (or registered readings), and sizes. To have an insight on the field customer meter accuracy, the sample of the meters should be tested under the field and float-valve flows (AL-Washali et al., 2020). Measurements of the network flows were obtained from the utility, and the flows of the float-valve were experimented from its fully open status to the closure level, with the network inflow. Based on Bernoulli's principle, in the fully open status of the float-valve, the flow that passes the customer meter is the network's flow. When the float-valve started to partially closes, the flow that passes the water meter is the flow of the float-valve. The samples were collected from the field and tested under these flows representing the actual flows in the field. The meters' accuracy was estimated for different heights in the tank and different openings of the float-valve, and accordingly the weighted meter accuracy was estimated. The data handling errors were estimated using utility data based on a sample audit conducted by the Sana'a water utility. Two assumptions were made with respect to the UC, similar to Zarqa, and two AL volumes were estimated. Accordingly, two RL volumes were calculated. The same methodology was also applied for the Mwanza water utility but based on a sample of 30 customer meters collected from the field and tested for two flows programmed in the bench test equipment.

3.2.2. Water and wastewater balance

The water and wastewater balance method was applied in only two cases, that is, for the Sana'a and Mwanza water supply systems. For Zarqa, the WWTP inflow data were not accessible because the WWTP was operated by the private sector. The application of the water and wastewater balance method to the Sana'a water supply system is discussed in AL-Washali et al. (2018). Firstly, factors α, β, and γ for the Sana'a water supply system were set to 5%, 0.8% and 5%, respectively. These factors were set based on Eq. (4), Eq. (5), and the data obtained from Sana'a water utility. Uncertainties and sensitivities of these factors are discussed in AL-Washali et al. (2018). Because the Sana'a water utility provides insufficient water to its customers, the supplementary supply through water tankers (Q_{ss}) was added to the balance and the AL was then estimated using the ALE equation, as presented in Eq. (10) (AL-Washali et al., 2018).

$$Q_{AL\ Sana'a} = 1.05Q_{ww} - 0.96Q_{bc} - 0.95Q_{ss} \tag{10}$$

The AL volume calculated using Eq. (10) only accounts for customers with both water and wastewater services. The AL rate per customer was calculated and then generalised for all water customers to obtain the total AL volume for the whole network. Subsequently, the RL volume was calculated from the total WL volume. Similarly, factor α for the Mwanza water supply system was assumed to be 7%; the low sensitivity of assuming this factor is discussed in AL-Washali et al. (2018). Factor β was estimated to be 0.63% based on utility data audits and factor γ was calculated to be 9% using Eq. (5). Accordingly, the AL in Mwanza was estimated using the ALE equation, as shown in Eq. (11), and available data for only four months and for customers with both water and wastewater services. The AL rate per customer was calculated and generalised for all water customers. The RL volume was then calculated from the WL volume.

$$Q_{AL\ Mwanza} = 1.07Q_{ww} - 0.92Q_{bc}, \tag{11}$$

3.2.3. Minimum night flow analysis

The MNF analysis was only applied in two cases: Zarqa and Mwanza. The application of the MNF method for the Sana'a water supply system was impossible because of the failure in completely separating a DMA and because the supplied water is not sufficient to reach the saturation condition, where all ground tanks in the DMA are completely full and the DMA becomes a continuous pressurised system during the test. For the Zarqa water supply system, the authors established a temporary DMA in the AL-Hashimia zone, which contains 1028 customers that are linked to the network via 978 service connections (AL-Washali et al., 2019b). For the measurement, an isolation valve, mechanical flow meter, and four pressure loggers were installed in the DMA and water was continuously supplied for five consecutive days from 08:00 am on 2 January 2015 to 8:00 am on 7 January 2016. It is believed that the DMA was saturated for at least one full day. There are no commercial, agricultural, or industrial activities in the zone; therefore, the legitimate night consumption was estimated based on the recommended assumption that 6% of the population is active and uses water for toilets at the rate of 5 l per flush, as discussed in Fantozzi and Lambert (2012) and Hamilton and McKenzie (2014). Sensitivity analysis of these assumptions are provided in the supplementary data of this paper. After estimating the net night flow in the DMA, the hourly leakage rate during the MNF hour can be found using Eq. (6). Extrapolating the hourly leakage rate to a daily leakage rate for the normal status in the DMA is only possible when the leakage-pressure relationship is considered. This relationship is considered in the NDF which was calculated using Eq. (7). Finally the RL rate was calculated using Eq. (8). With respect to the Mwanza water supply system, a DMA has been already established in the Kenyatta zone, which contains 64 connections for domestic, commercial, and industrial customers. For this measurement, an ultrasonic water meter with a pressure recorder was installed to measure the flow and pressure at the inlet of the DMA, four pressure recorders were installed at critical points of the DMA, and six recorders were installed at different points in the network to estimate the network pressure. The water was then continuously supplied to the DMA for three consecutive days from 10:45 am on 19 December 2015 to 10:30 am on 21 December 2015. Because this DMA is small, all customer meters in the DMA were read twice at night each day at an interval of two hours to estimate the legitimate night consumption in the DMA. After estimating the net night flow in the DMA, the NDF was calculated and the RL was estimated using Eqs. (7) and (8), respectively.

3.2.4. Component analysis of the leakage

The component analysis of the leakage, or the BABE concept, was applied in all the three cases in this study using a spreadsheet model, that is, 'Real Loss Component Analysis: a Tool for Economic Water Loss Control', developed by the Water Research Foundation, USA; (Sturm et al., 2014). The case study data for the reported bursts as well as unreported leaks that were discovered based on the leakage detection

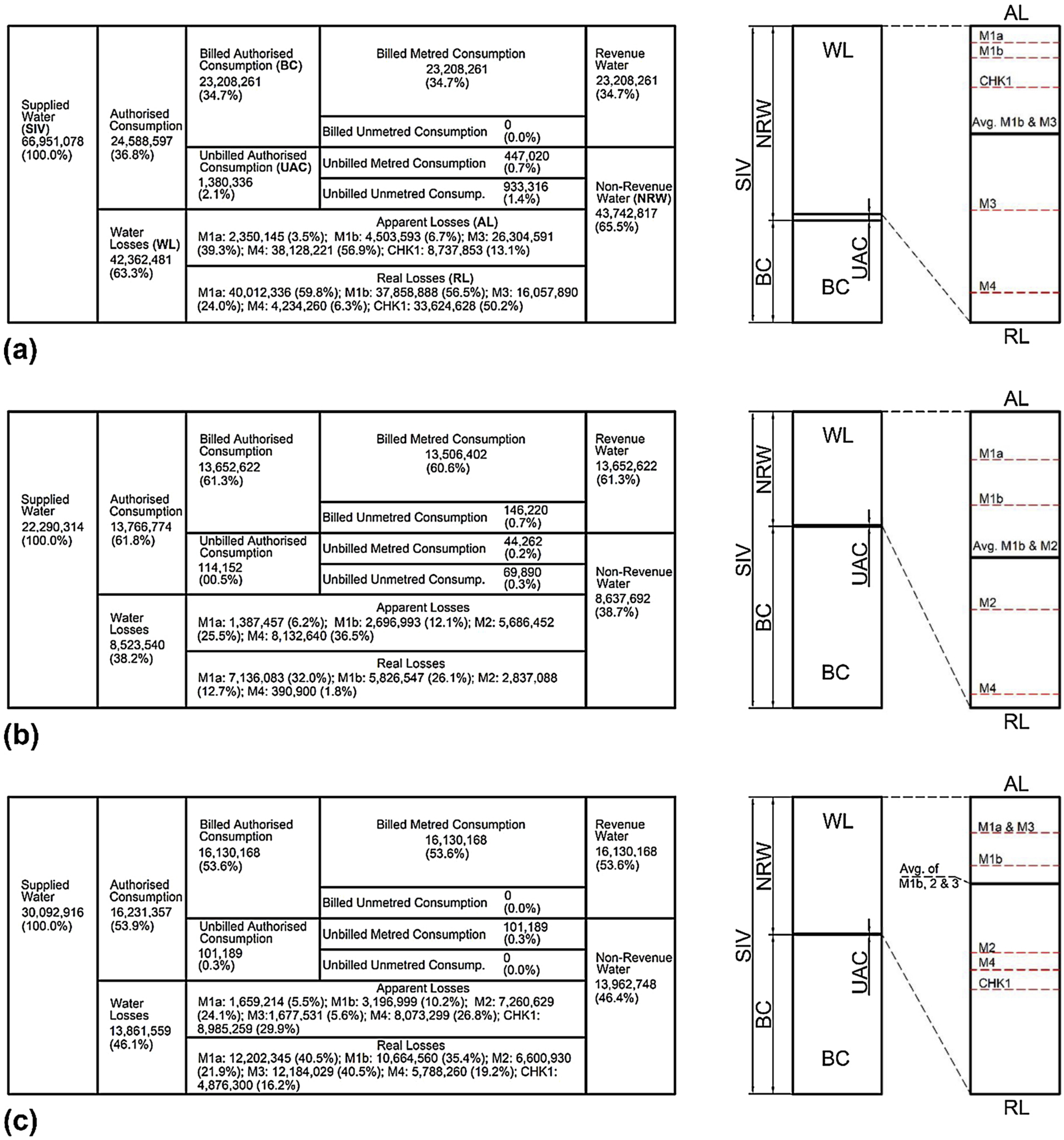

Fig. 1. IWA standard water balance in m^3/yr and % (left) and scaled water loss breakdown (right): (a) Zarqa, Jordan, (b) Sana'a, Yemen, and (c) Mwanza, Tanzania. M_{1a} and M_{1b}: top-down water balance including the unauthorised consumption of 0.25% of the SIV and 10% of the billed consumption, respectively; M_2: water and wastewater balance method; M_3: minimum night flow analysis method; M_4: component analysis of the leakage method; and CHK1: $M_{1b} - M_4 = M_3$.

surveys were entered in the model. The leakage was then estimated based on the spreadsheet calculations. All the parameters used in the model are input data of the case studies apart from the flow rate whose default value was used as it is not the influencing factor in this analysis (Lambert, 1994). Other parameters used in the model were infrastructure condition factor based on the age of the network; a value of 1 for the N_1 leakage-pressure exponent; and the length of the private line between the customer meter and private boundary of the customer, that is, 0 m, 0 m, and 13.3 m for Sana'a, Zarqa, and Mwanza, respectively.

3.3. Results of the water loss component assessment

Fig. 1 shows the results of the four WL component assessment methods for the three case studies. The figure shows the IWA standard water balance for the three cases on the left side (in m^3/yr and %). On the right side of Fig. 1, the breakdown of the WL into AL and RL is shown in a scaled plot. There are two columns: the left one presents the portions of the SIV, BC, and NRW (difference between SIV and BC). If we deduce the UAC from the NRW volume, we obtain the WL volume. Subsequently, we can break down the WL into AL and RL (far-right rectangular column in Fig. 1a). To break down the WL into AL and RL, we use different methods, where each method estimates the AL and RL volumes differently. Thus, the line between AL and RL is drawn differently. For example, based on method 1a (M_{1a}), the WL consists of a very small amount of AL and the remaining part is RL; the line is plotted accordingly (red dotted line M_{1a}). This is similar for the other methods, that is, M_{1b}, M_2, M_3, and M_4. The average of M_{1b} and M_3 is plotted as black line dividing the WL volume into two rectangular parts, where the upper part represents the AL and the lower part presents the RL.

Based on Fig. 1, the different methods yield different WL components. As expected, the top-down water balance method assuming the UAC to be 0.25% of the supplied water (M_{1a}) yields the smallest AL volume in all three cases because the UAC in the case studies is considerably higher than this assumption, which is based on a different context in Europe. Therefore, M_{1a} significantly overestimates the RL volume. When increasing the assumption of the UAC to 10% of the BC, as in M_{1b}, the method yields relatively higher AL volumes, which are closer to the actual situation of these cases, where UC is common. Nevertheless, it is still unclear how close the results of this method are to the actual AL and RL volumes in the case study systems. The assumption that the UC is 10% of the BC is not data-based and generalising it for developing countries is not justified because it could significantly differ from one case to another. Based on Fig. 1, M_{1b} represents the second smallest estimations of the AL in all cases (given that M_3 in Mwanza is not representative for the entire network). Because M_{1b} often estimates a smaller AL than M_2 and M_3, this could indicate that M_{1b} underestimates the AL volume and overestimates the RL volume.

Likewise, the water and wastewater balance method (M_2) probably overestimates the AL volume and therefore underestimates the RL volume because its line is located below the average line in the two cases in Fig. 1b and c, that is, for Sana'a and Mwanza, respectively. The MNF analysis (M_3) of the two case studies in Fig. 1a and c for Zarqa and Mwanza is inconsistent because generalizing the RL level of a small area (DMA) for the entire network is associated with significant uncertainties (AL-Washali et al., 2019b). The DMA cannot sufficiently represent the infrastructure, pressure, and consumption of the entire network. The leakage in a DMA in Mwanza with only 64 customers is not representative; the DMA in Zarqa is also not completely representative.

On the other hand, the component analysis of the leakage (BABE; M_4) yields the smallest RL volume in the three cases and therefore overestimates the AL volume. The M_4 estimates the volumes of the bursts that are reported to the utility for repair work, unreported bursts that are discovered based on the leakage detection surveys, and background leaks that cannot be detected by the detection campaigns and continuously run. The records of all burst events in the whole systems were considered in the analysis based on the maintenance records and maintenance software of the utilities. These data are of good quality because burst events have to be repaired by the utility crew and the maintenance software does not approve or close an administration order for a maintenance team unless technical and geo-referenced data are provided. Therefore, the underestimation of the leakage volume is due to shortcomings of this method with respect to estimating the volume of background leaks and also due to different policies and technologies used for leakage detection in the case studies analysed in this work compared with the cases for which this method was initially developed.

A logical check was suggested by Thornton et al. (2008) that the difference of leakage volume of the top-down water balance and the component analysis of leakage (BABE) is closely equal to the leakage volume in the MNF method (CHK1: $M_{1b} - M_4 = M_3$). This check did not yield a close value, neither in Zarqa nor Mwanza, but rather different results, as shown in Fig. 1.

The comparison of the estimated AL and RL volumes with the actual volumes is impossible, except for one case, that is, if the whole network is divided in DMAs and the flow and pressure of these DMAs are measured throughout the year. This is not the case in the three case studies and will not be the case in the seen future, because of limitations in the capacity and resources of these utilities. Therefore, the results of the WL component assessment methods cannot be validated based on field data. However, the average obtained from the methods M_{1b}, M_2, and M_3 provides a reasonable result in the three cases, including comparing it with the subjective expectations of AL and RL portions of SIV, by the specialists in the utilities, which are 25%, 38%; 23%, 15%; and 43%, 11% for Zarqa, Sana'a and Mwanza respectively.

4. Uncertainty analysis

Uncertainty analysis was performed to provide insights into the accuracies and sensitivities of the method as well as the consistency of the methods' outputs. The error propagation theory was used for this analysis and the uncertainties of AL and RL were calculated using Eq. (12) (Taylor, 1997):

$$\Delta U = \sqrt{(\delta U/\delta A)^2\,(\Delta A)^2 + (\delta U/\delta B)^2\,(\Delta B)^2 + (\delta U/\delta C)^2\,(\Delta C)^2} \tag{12}$$

where A, B, and C are independent measurable quantities that are used to obtain a value of a calculated quantity U; $\delta U/\delta$ is the partial derivative of the variable U with respect to an independent parameter (A, B, or C); and ΔA, ΔB, and ΔC are the uncertainties of the variables A, B, and C. The results of the error propagation theory were also verified with other uncertainty analysis methods, such as variance analysis (Thornton et al., 2008) and Monte Carlo simulation (Rubinstein and Kroese, 2016), which provided the same uncertainties.

To estimate the uncertainties in the AL and RL, all components of the standard water balance must be assigned an uncertainty. A supplementary file of this paper presents the uncertainty in the water balance for all methods and the three case studies. The water balance uncertainties for Zarqa, Sana'a, and Mwanza were assigned based on the estimations and discussions with specialists of these utilities. As widely applied by IWA WL specialists (Lambert et al., 2014), the uncertainty level is assigned to the water balance component based on the confidence level of the input data. Accordingly, the uncertainty of the SIV is assumed to be ± 5% for Zarqa based on the production meter status. The system is almost fully metered and the uncertainty of the BC is thus zero because meter and billing uncertainties are considered for the AL component. The random and systematic errors associated with estimating the amount of the UAC are assumed to be ± 5% of the measured volume and ± 20% for the unmeasured volume based on the confidence of the specialists of the utility with respect to these figures. The confidence with respect to estimating the data handling errors and inaccuracies of customer meters are also assumed to be ± 20% according to the expectations of the specialists in the water utility. The assigned uncertainties were the same when applying different methods for the WL component assessment. These uncertainties are aggregated in the final calculated uncertainties of AL and RL. Two variables remained unassigned with uncertainties, RL and UC; one of them must be assigned an uncertainty and then the uncertainty of the other variable can be calculated depending on the applied WL component assessment method.

For the top-down water balance, the UC must be assigned an arbitrary uncertainty. Therefore, the UC was assigned an uncertainty of ± 200% and ± 100% for M_{1a} and M_{1b}, respectively, because the assumption of the UC based on these methods does not fit well the case studies. Based on these uncertainties, the aggregated uncertainty of RL is ± 9% and ± 11% for M_{1a} and M_{1b}, respectively. Similarly, the uncertainties of the water balance were calculated for RL and AL for all methods and the three case studies, as elaborated in the supplementary file. Table 2 shows the volumes and uncertainties of AL and RL estimated using different methods (M_{1a}, M_{1b}, M_2, M_3, and M_4) for Zarqa, Sana'a, and Mwanza.

Regarding the water balance method (M_{1a}), the propagated and aggregated errors of the RL volume are only ± 9%, ± 7%, and ± 13% for Zarqa, Sana'a, and Mwanza, respectively. Similarly, for M_4, the aggregated errors of the AL volume are ± 24%, ± 11%, and ± 145% for Zarqa, Sana'a, and Mwanza, respectively, after assigning an uncertainty level to the RL volume of ± 200% because this method greatly underestimates the RL volume, as discussed in Section 3.3.

Interestingly, the methods M_{1a} and M_4 provide the least accurate AL and RL estimations, as discussed above, but they also have relatively low levels of uncertainties (Table 2). This suggests that the uncertainty analysis does not indicate how accurate the outputs of the methods or the level of validity of each method are. In fact, for the two WL components (AL and RL), a low level of uncertainty will always be the case when the volume of the final calculated component (e.g. RL) is extremely larger than the volume of the other component (e.g. AL); and high level of uncertainty will always be the case when the volume of the final calculated component is significantly smaller than that of the other component. Further illustrating this fact, Fig. 2 shows that when the AL is more significant in the network, the aggregated errors of the water balance reach a substantial portion of RL and thus the RL becomes more uncertain through the top down water balance. In contrast, when the AL is insignificant, the aggregated errors of the water balance become less sensitive. In conclusion, it is notable that uncertainty analysis helps in analysing the sensitivities of the inputs of the methods and improving the estimations of the individual methods, but it does not indicate the validity or accuracy of the methods.

5. Implication of the water loss component assessment

The impact of the WL component assessment on WL reduction planning can be illustrated and clarified. In contrast to the AL, economic analysis tools for leakage reduction planning are available. Therefore, the impact of the WL component assessment on the leakage reduction planning was analysed in this study using the 'Real Loss Component Analysis: a Tool for Economic Water Loss Control' model (Sturm et al., 2014). The model is a spreadsheet with entry data including water balance, cost and financial data and failures and their characteristics. It can be applied to analyse the benefits of different leakage reduction options for continuous and intermittent supply. All the data used in the model are entered except the flow rates of the failures which are not sensitive in the analysis (Lambert, 1994). Accordingly, the water and monetary potential savings were calculated for each WL assessment method and three leakage reduction interventions: (i) minimizing the response and repair time of bursts in the network, (ii) cost and benefits of conducting leakage detection surveys using acoustic and noise-tracking technologies, and (iii) potential savings based on the reduction of the average pressure of the network.

Minimizing the response and repair time of bursts has an influence on the reduction of the runtime of the leakage and is considered in the model. The savings due to the pressure reduction are estimated using the pressure–leakage relationship, which is assumed to be linear (McKenzie, 2003; Morrison et al., 2007). The potential savings when conducting regular leakage detection surveys are analysed differently in the model. First, the potentially avoidable and unavoidable leakage volumes are computed using the BABE concept, as elaborated in Section 2.4. The frequency of the proactive leakage detection surveys is then estimated using Eqs. (13) and (14) (Lambert and Fantozzi, 2005):

$$EIF = \sqrt{0.789 \times \frac{CI}{CV \times RR}} \tag{13}$$

$$EP = 100 \times 12/EIF \tag{14}$$

where EIF (months) is the economic intervention frequency based on the leakage detection surveys, CI represents the intervention cost (\$/km), CV represents the variable cost (\$/m^3), RR is the rate of rise of unreported leakage (m^3/km mains/d/yr), and EP is the economic percentage of system to be surveyed annually. Eventually, the monetary value of these leakage reduction interventions is calculated using the variable cost of the water in each system.

The influence of the WL component assessment on prioritizing and planning leakage reduction measures is presented in Fig. 3. The left side of Fig. 3 shows the annual cost of WL calculated based on the different methods. The cost of AL differs from the cost of RL. The cost of RL is valued based on the production cost of water, while the cost of AL is the average actual revenue (i.e. price) per cubic metre. Therefore, the total cost of WL varies because the AL and RL volumes and the costs of AL and RL differ from one method to another. Based on the consideration of only M_{1b}, M_2, and M_3 because they yield more reasonable results, as discussed in Section 3.3, the annual cost of the WL varies from 12.0 to 21.5 million USD for Zarqa, from 3.5 to 4.2 million USD for Sana'a, and from 3.3 to 3.6 million USD for Mwanza. This indicates the sensitivity of the WL component assessment with respect to estimating the cost of the WL and consequently all economic calculations that use this input including the economic level of the WL.

The monetary value of the potential savings of the leakage reduction measures was also analysed for all methods (Fig. 3, right side). Based on Fig. 3a and considering only methods with relatively reasonable results, as discussed in Section 3.3 (i.e. M_{1b} and M_3 in Zarqa), the potential savings based on the reduction of the average pressure in Zarqa network by one bar (from 3.3 to 2.2 bar) vary from 1.2 to 2.7 million USD, respectively. The potential savings based on the adoption of the active leakage control (ALC) using regular leakage detection surveys in the entire network every 10.5 months vary from 2.5 to 7.7 million USD. The potential savings based on the reduction of the response and repair time of the reported bursts from the annual average of 2 d to 3 h are 0.4 million USD and are not affected by the component assessment methods

Table 2
Uncertainties of the AL and RL for the different methods (million m^3 and %).

Method			Zarqa		Sana'a		Mwanza	
			AL	RL	AL	RL	AL	RL
Water Balance	M_{1a}	(Mm^3)	2.4	40.0	1.4	7.1	1.7	12.2
		(Δ ± %)	26%	9%	16%	7%	16%	13%
	M_{1b}	(Mm^3)	4.5	37.9	2.7	5.8	3.2	10.7
		(Δ ± %)	53%	11%	51%	25%	51%	21%
W&WW Balance	M_2	(Mm^3)			5.7	2.8	7.3	6.6
		(Δ ± %)			18%	40%	24%	35%
MNF	M_3	(Mm^3)	26.3	16.1			1.7	12.2
		(Δ ± %)	22%	30%			236%	30%
BABE	M_4	(Mm^3)	38.1	4.2	8.1	0.4	8.1	5.8
		(Δ ± %)	24%	200%	11%	200%	145%	200%

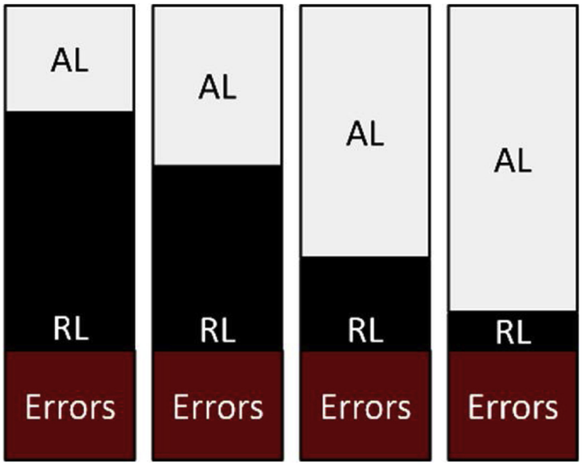

Fig. 2. Aggregated errors of the water balance components form a bigger portion of RL when the AL is more significant.

because it can only be conducted using M_4, that is, the component analysis of the leakage. Finally, the potential savings based on the adoption of all these measures cannot be the sum of the potential of these measures because each option is influenced by other options. For example, the pressure reduction lowers the rate of bursts in the network but undermines the potential of leakage detection surveys because the leakage noise will be harder to hear and detect (AL-Washali et al., 2019b).

Similarly, when considering M_{1b} and M_2 for Sana'a (Fig. 3b, right side), the potential savings based on the reduction of the average pressure by 0.2 bar (from 1 to 0.8 bar) vary from 0.2 to 0.4 million USD. The potential savings based on the adoption of active leakage control using regular leakage detection surveys in the entire network every 8.9 months vary from 0.7 to 1.7 million USD. The potential savings based on the reduction of the response and repair time of the reported bursts from the annual average of 2.3 to 0.5 d are 0.02 million USD. Based on considering M_{1b}, M_2, and M_3 for Mwanza, the potential savings based on the reduction of the average pressure in the Mwanza network by 2.0 bar (from 5.8 to 3.8 bar) vary from 0.5 to 1.0 million USD. The potential savings based on the adoption of active leakage control using regular leakage detection surveys in the entire network every 10.7 months vary from 0.1 to 1.4 million USD. The potential savings based on the reduction of the response and repair time of the reported bursts from the annual average of 2.0 to 0.5 d are 0.2 million USD.

Based on Fig. 3, it can be concluded that the feasibility of leakage detection surveys is highly influenced by the component assessment. The feasibility of the pressure management is also influenced but to a lesser extent. The feasibility of the response and repair time reduction is not affected because it is only estimated using one method, that is, the

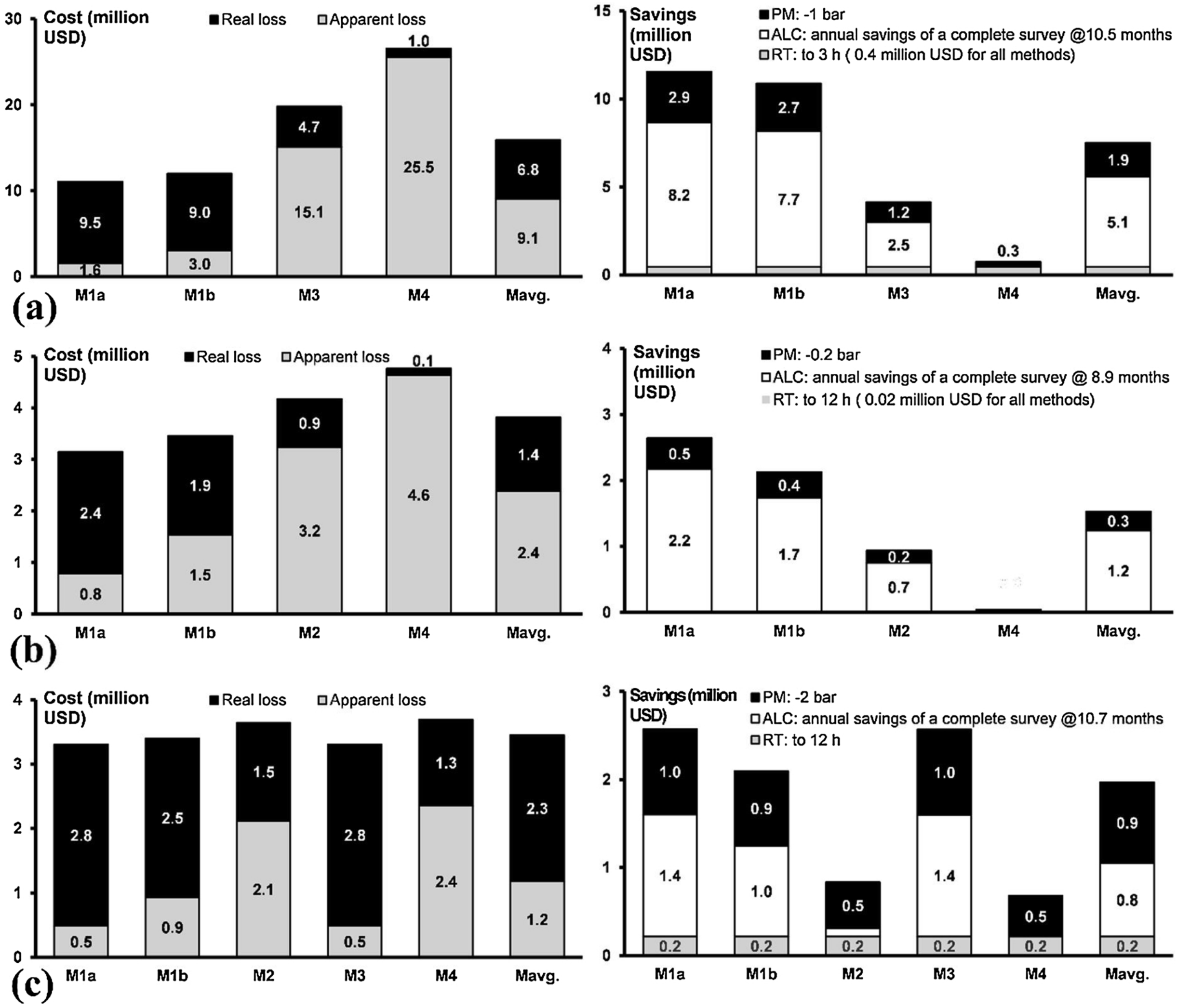

Fig. 3. Cost of the water loss components in USD (left) and potential savings based on the reduction of the leak repair time (RT), leak detection surveys (ALC), and pressure management (PM) in USD according to different component assessment methods (right): (a) Zarqa, Jordan, (b) Sana'a, Yemen, and (c) Mwanza, Tanzania.

component analysis of the leakage. These results confirm that economic planning is significantly affected by the WL component assessment and its uncertainties, leading to unstable and uncertain economic models and WL reduction plans.

6. Conclusions

A review of the state-of-the-art methods for WL component (AL and RL) assessment is presented in this paper. These methods were applied to three cases in developing countries and economic and uncertainty analyses were performed. The main conclusions of this study are the following:

- Investing in improvements of the top-down methods is demanding and promising. The top-down water balance will benefit from developing an objective methodology for estimations of the UC volume because the current assumptions are both critical and arbitrary. The accuracy of this method depends on how applicable its assumptions are. In the analysed cases, this method underestimates the AL volume and overestimates the RL volume. Estimating the AL volume using the water and wastewater balance method yields closer results to the expectations of the specialists in these utilities. However, the method could be overestimating the AL volume because it estimates the AL volume more than the average volume of the methods. Applying each method requires verification for the factors and assumptions in each method and their sensitivities and uncertainties. However, if such analysis cannot be carried out, taking the average of these two methods is a practical approach in intermittent supply systems..
- Conducting MNF analysis in one or several small areas in the network (DMAs) and extrapolating it to the entire network might be justifiable in some cases, but it is not very rational because every DMA differs in terms of the mains length, service connections, pressure, and burst frequencies. The MNF analysis is more suitable for the DMA scale than for a system-wide scale with respect to the interventions and identification and repair of unreported leaks. The component analysis of the leakage method (BABE) remains the only way to break down the leakage into subcomponents, enabling the water utilities to understand the nature and behaviour of the leakage in their systems. However, the component analysis of the leakage analyses only a small portion of the leakage and cannot be used for WL component assessment.
- The results show that WL component assessment has significant uncertainties, which in turn affect the cost of WL and substantially impact the planning of RL and AL minimisation measures. Addressing this issue needs more investigation on how the WL component assessment can be improved. Field observations that could help to validate and calibrate the methods are not obtainable unless the entire network is divided into DMAs to conduct regular MNF measurements throughout the year, which is very costly and unlikely, especially in developing countries. On the other hand, the uncertainty analysis helps to improve the output of the individual methods but not the methods' accuracies. Therefore, assessing the WL components by using at least two methods should improve the prioritisation, economic modelling, monitoring, and benchmarking of the WL.
- For intermittent supply systems in developing countries, the average volume of the AL from the top-down water balance and water and wastewater balance methods should be used to establish the standard water balance. The RL can then be further broken down using the component analysis of the leakage. Based on this methodology, leakage reduction interventions can be planned and prioritised for the entire network. Subsequently, MNF analysis can be used on a DMA-scale in the implementation phase to separately intervene, monitor, and reduce the leakage in each DMA.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2019.104515.

References

AL-Washali, T., Mahardani, M., Sharma, S., Arregui, F., Kennedy, M., 2020. Impact of the float-valve on the water meter performance under intermittency and continuity conditions. In preparation.
AL-Washali, T., Sharma, S., AL-Nozaily, F., Haidera, M., Kennedy, M., 2019a. Monitoring the non-revenue water performance in intermittent supplies. Water 11 (6), 1220.
AL-Washali, T., Sharma, S., Kennedy, M., 2016. Methods of assessment of water losses in water supply systems: a review. Water Resour. Manage. 30 (14), 4985–5001.
AL-Washali, T.M., Sharma, S.K., Kennedy, M.D., 2018. Alternative method for non-revenue water component assessment. J. Water Resour. Plan. Manage. 144 (5), 04018017.
AL-Washali, T.M., Sharma, S.K., Kennedy, M.D., AL-Nozaily, F., Mansour, H., 2019b. Modelling the leakage rate and reduction using minimum night flow analysis in an intermittent supply system. Water 11 (1), 48.
Alegre, H., Baptista, J.M., Cabrera Jr, E., Cubillo, F., Duarte, P., Hirner, W., Merkel, W., Parena, R., 2016. Performance Indicators for Water Supply Services. IWA Publishing, London, UK.
Alegre, H., Hirner, W., Baptista, J., 2000. Performance Indicators for Water Supply Services. Manual of Best Practice. IWA Publishing, London, UK.
Arregui, F., Cabrera Jr, E., Cobacho, R., 2007. Integrated Water Meter Management. IWA Publishing, London, UK.
Ashton, C., Hope, V., 2001. Environmental valuation and the economic level of leakage. Urban Water 3 (4), 261–270.
AWWA, 2009. Loss Control Programs-Manual of Water Supply Practices, M36. American Water Works Association, Denver, USA.
AWWA, 2016. M36 Water Audits and Loss Control Programs, fourth edition. American Water Works Association, USA.
Connor, R., Renata, A., Ortigara, C., Koncagül, E., Uhlenbrook, S., Lamizana-Diallo, B.M., Zadeh, S.M., Qadir, M., Kjellén, M., Sjödin, J., 2017. Wastewater: The Untapped Resource, The United Nations World Water Development Report (9231002015).
Deuerlein, J.W., 2008. Decomposition model of a general water supply network graph. J. Hydraul. Eng. 134 (6), 822–832.
Dighade, R., Kadu, M., Pande, A., 2014. Challenges in water loss management of water distribution systems in developing countries. Int. J. Innov. Res. Sci. Eng. Technol. 3 (6), 13838–13846.
Eugine, M., 2017. Predictive leakage estimation using the cumulative minimum night flow approach. Am. J. Water Resour. 5 (1), 1–4.
European Commission, D. G. f. t. E, 2015. EU Reference Document Good Practices on Leakage Management WFD CIS WG PoM: Main Report. Brussels, European Union.
Fanner, P., Thornton, J., 2005. The importance of real loss component analysis for determining the correct intervention strategy. In: Proceedings of IWA Water Loss 2005 Conference. Halifax, Nova Scotia, Canada.
Fantozzi, M., Lambert, A., 2012. Residential night consumption–assessment, choice of scaling units and calculation of variability. In: IWA Water Loss Conference. Manila, Philippines. pp. 26–29.
Farah, E., Shahrour, I., 2017. Leakage detection using smart water system: combination of water balance and automated minimum night flow. Water Resour. Manage. 31 (15), 4821–4833.
Farley, M., Trow, S., 2003. Losses in Water Distribution Networks. IWA Publishing, London, UK.
Farley, M., Wyeth, G., Ghazali, Z.B.M., Istandar, A., Singh, S., Dijk, N., Raksakulthai, V., Kirkwood, E., 2008. The Manager's Non-revenue Water Handbook: A Guide to Understanding Water Losses. Ranhill Utilities Berhad and the United States Agency for International Developement, Bangkok, Thailand.
Frauendorfer, R., Liemberger, R., 2010. The Issues and Challenges of Reducing Non-revenue Water. Asian Development Bank, Metro Manila, Philippines.
Galdiero, E., De Paola, F., Fontana, N., Giugni, M., Savic, D., 2015. Decision support system for the optimal design of district metered areas. J. Hydroinformatics 18 (1), 49–61.
Hamilton, S., McKenzie, R., 2014. Water Management and Water Loss. IWA Publishing.
Kanakoudis, V., Tsitsifli, S., 2014. Using the bimonthly water balance of a non-fully

monitored water distribution network with seasonal water demand peaks to define its actual NRW level: the case of Kos town, Greece. Urban Water J. 11 (5), 348–360.

Kanakoudis, V., Tsitsifli, S., Papadopoulou, A., 2012. Integrating the carbon and water footprints' costs in the water framework directive 2000/60/EC full water cost recovery concept: basic principles towards their reliable calculation and socially just allocation. Water 4 (1), 45–62.

Kesavan, H., Chandrashekar, M., 1972. Graph-theoretical models for pipe network analysis. J. Hydraul. Div. 98 (2), 345–364.

Lambert, A., 1994. Accounting for losses: the bursts and background concept. Water Environ. J. 8 (2), 205–214.

Lambert, A., 2019. What do we know about pressure-leakage relationships in distribution systems. IWA Conference in Systems Approach to Leakage Control and Water Distribution System Management, Brno, Czech Republic.

Lambert, A., 2009. Ten years experience in using the UARL formula to calculate infrastructure leakage index. In: Proceedings of IWA Specialized Conference: Water Loss 2009. Cape Town, South Africa. pp. 189–196.

Lambert, A., Brown, T.G., Takizawa, M., Weimer, D., 1999. A review of performance indicators for real losses from water supply systems. J. Water Supply Res. Technol. 48 (6), 227–237.

Lambert, A., Charalambous, B., Fantozzi, M., Kovac, J., Rizzo, A., St John, S.G., 2014. 14 years' experience of using IWA best practice water balance and water loss performance indicators in Europe. In: Proceedings of IWA Specialized Conference: Water Loss 2014. Vienna.

Lambert, A., Fantozzi, M., 2005. Recent advances in calculating economic intervention frequency for active leakage control, and implications for calculation of economic leakage levels. Water Sci. Technol. Water Supply 5 (6), 263–271.

Lambert, A., Fantozzi, M., Shepherd, M., 2017. FAVAD pressure & leakage: how does pressure influence N1? In: IWA Water Efficient 2017 Conference, 18th to 20th July 2017. Bath, UK.

Lambert, A., Hirner, W., 2000. Losses From Water Supply Systems: A Standard Terminology and Recommended Performance Measures. IWA Publishing, London, UK.

Lambert, A., Lalonde, A., 2005. Using practical predictions of economic intervention frequency to calculate short-run economic leakage level, with or without pressure management. In: Proceedings of IWA Specialised Conference "Leakage 2005". Halifax, Nova Scotia, Canada. pp. 310–321.

Lambert, A., Taylor, R., 2010. Water Loss Guidelines. Water New Zealand, New Zealand.

Liemberger, R., Farley, M., 2004. Developing a nonrevenue water reduction strategy part 1: investigating and assessing water losses. In: Proceedings of IWA Specialized Conference: the 4th IWA World Water Congress Marrakech. Morocco.

Liemberger, R., Wyatt, A., 2018. Quantifying the global non-revenue water problem. Water Sci. Technol. Water Supply 19 (3), 831–837.

May, J., 1994. Pressure dependent leakage. World Water and Environmental Engineering. Water Environment Federation, Washington D.C.

McKenzie, R.S., 2003. Water Demand Management Cookbook. Rand Water, Johannesburg, South Africa.

Molinos-Senante, M., Mocholí-Arce, M., Sala-Garrido, R., 2016. Estimating the environmental and resource costs of leakage in water distribution systems: a shadow price approach. Sci. Total Environ. 568, 180–188.

Morrison, J., Tooms, S., Rogers, D., 2007. District Metered Areas, Guidance Notes. International Water Association (IWA), Specialist Group on Efficient Operation and Management of Urban Water Distribution Systems, UK.

Mutikanga, H., 2012. Water Loss Management: Tools and Methods for Developing Countries, PhD Thesis. IHE-Delft, Institute for Water Education, Delft, The Netherlands.

Mutikanga, H., Sharma, S., Vairavamoorthy, K., 2011. Assessment of apparent losses in urban water systems. Water Environ. J. 25 (3), 327–335.

Mutikanga, H.E., Sharma, S.K., Vairavamoorthy, K., 2012. Methods and tools for managing losses in water distribution systems. J. Water Resour. Plan. Manage. 139 (2), 166–174.

Pearson, D., Trow, S., 2005. Calculating economic levels of leakage. In: IWA Water Loss 2005 Conference. Halifax, NS, Canada.

Puust, R., Kapelan, Z., Savic, D., Koppel, T., 2010. A review of methods for leakage management in pipe networks. Urban Water J. 7 (1), 25–45.

Rubinstein, R.Y., Kroese, D.P., 2016. Simulation and the Monte Carlo Method. John Wiley & Sons.

Seago, C., Bhagwan, J., McKenzie, R., 2004. Benchmarking leakage from water reticulation systems in South Africa. Water SA 30 (5), 25–32.

Sturm, R., Gasner, K., Wilson, T., Preston, S., Dickinson, M.A., 2014. Real Loss Component Analysis: A Tool for Economic Water Loss Control. Water Research Foundation, Denver, USA.

Taylor, J., 1997. Introduction to Error Analysis, the Study of Uncertainties in Physical Measurements. University Science Books, New York, USA.

Thornton, J., Sturm, R., Kunkel, G., 2008. Water Loss Control. McGraw Hill Professional, New York, USA.

Van Zyl, J., Cassa, A., 2014. Modeling elastically deforming leaks in water distribution pipes. J. Hydraul. Eng. 140 (2), 182–189.

Van Zyl, J., Lambert, A., Collins, R., 2017. Realistic modeling of leakage and intrusion flows through leak openings in pipes. J. Hydraul. Eng. 143 (9), 04017030.

Vermersch, M., Carteado, F., Rizzo, A., Johnson, E., Arregui, F., Lambert, A., 2016. Guidance Notes on Apparent Losses and Water Loss Reduction Planning. LeaksSuit Library, UK.

Vermersch, M., Rizzo, A., 2008. Designing an action plan to control non-revenue water. Water 21, 39–41.

Wyatt, A.S., 2010. Non-revenue Water: Financial Model for Optimal Management in Developing Countries, RTI Press No. MR-0018-1006 Durham, USA.