Leakage estimation in water networks based on the BABE and MNF analyses: a case study in Gavankola village, Iran

Saeid Mohammadzade Negharchi and Rouzbeh Shafaghat

ABSTRACT

Calculating the water loss and leakage in the water distribution networks (WDNs) is performed for various reasons such as monitoring and optimizing, active control, estimating economical damage, and predicting the demand in the network development plans. In this research, two leakage calculation methods including Background and Bursts Estimates (BABE) and minimum night flow (MNF) have been evaluated for a rural network in the north of Iran with a high non-revenue water (NRW) percentage of 47%. Initially, the data related to the inlet flow rate of the network and the average pressure at zone was measured using ultrasonic flow meters and pressure transmitter, respectively. Then, remote data loggers collected these data. With the water loss analyses based on the BABE method (annually) and based on the MNF technique (every 10 minutes), the average leak was found to be 1.45 and 1.105 Lit/s, respectively. Also, according to hydraulic and consumption conditions, the highest frequency of MNF occurrence was observed at 00:00 and 05:00. Moreover, the effects of legitimate night-time consumption (LNC) and leakage exponent (N) were evaluated. The results indicate that determining the LNC, especially in the networks in which the domestic customers use private tanks, is significantly important.

Key words | BABE analysis, leakage, legitimate customer night use, minimum night flow analysis, water distribution network, water loss

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HIGHLIGHTS

- Two leak estimation methods, including BABE and MNF, were evaluated for a rural water network in Iran.
- Effect of various water distribution pressures on the consumption pattern is presented.
- Effect of legitimate night-time consumption (LNC) and leakage exponent (N) on the obtained results are investigated.
- Use of private tanks by domestic customers is a significantly important parameter in leakage estimation.

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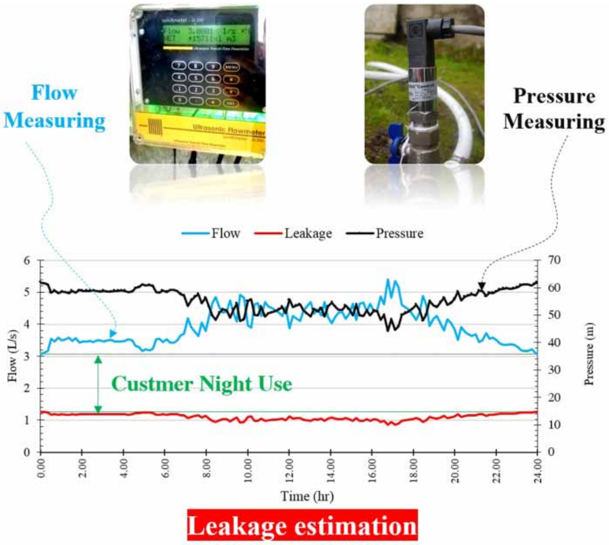
GRAPHICAL ABSTRACT



INTRODUCTION

The annual water loss volume in the world is considerable. It is estimated that in each year 126 billion m^3 of water with a price of 39 billion US dollars are wasted (Taha *et al.* 2020). A major part of this water loss happens due to the leakage in the water distribution networks (WDNs), which is enough to provide service to 200 million people (Norouzi *et al.* 2019). The created leaks in the systems not only affect the water and energy losses in the network (due to the high energy loss of pumping) but also have some negative effects on the water quality. This happens because of the penetration of pollutants in the low-pressure conditions of the network (Colombo & Karney 2002).

Considering the importance of water loss and leakage in the WDNs, nowadays different methods have been presented for estimating water loss (Al-Washali *et al.* 2019). Each of these techniques requires specific initial data and information, which can include the customer's information and their consumption data, the amount of produced water, and the information on the network components. The latter includes the length of distribution network pipes, number of connections, storage conditions, the measured pressure or flow rates, and the data regarding the pipe breaks and bursts. Certainly, the accuracy of the input data has a significant influence on the precision of the calculations (Guideline 556 of Iran MOE 2017).

Generally, leakage in the WDNs occurs due to the low quality of materials in pipes or other network components, errors in design, inappropriate maintenance, high pressure in the network, and pipe break and bursts (Guideline 556 of Iran MOE 2017). The methods of leakage reduction include passive control, like repairing the daily pipe breaks and bursts, and active control of leaks, such as the detection of the leakage exact location, repairing it, replacing the damaged pipelines, and pressure management (Baader *et al.* 2011). The water service companies have at least ten reasons for justifying the raising of the leakage management budget; that is, the efficiency of operating costs, the efficiency of capital cost, enhanced metering and billing, reduced health risks, increased supply safety, less infrastructure damages, lower stress on sewers, improved customer satisfaction, advertising and costomers' willingness to pay, and reduced ecological stress (Baader *et al.* 2011). Besides, the World Bank recommends non-revenue water (NRW) of less than 23% (Ndunguru & Hoko 2016).

Researchers and water supply companies have been actively investigating and preventing leakage for more than two decades. In the 1990s, the development of a model for recognizing the components of real water loss was considered necessary by the UK Leakage Control Initiative. This method, which was introduced as the Background and Bursts Estimates (BABE) method, recognized and estimated the real water loss as leakage in the background, burst, reported overflows and leaks at the reservoirs, unreported bursts, overflows at the customers' private tanks, main lines, distribution, connections, and internal network lines of customers (Lambert & Morrison 1996; McKenzie & Seago 2003). In the UK, background leakage is defined as the sum of all leakages with lower flow rates than 0.5 m^3/h in the pressure of 50 meters; otherwise, they are considered as bursts (García *et al.* 2008).

Water loss due to background leaks can remain undetected for a long time and plays a significant role in real water loss. In 1994, the BABE method was developed for considering the influence of pressure on the leakage and led to the introduction of a pressure correction factor (Lambert & Morrison 1996). In 1999, based on the concepts of the BABE method, the BENCHLEAK model was developed in South Africa for estimating leakage and some performance parameters. In the McKenzie model, burst with leaks lower than 0.25 m^3/h are defined as background leakage (McKenzie 1999). Increased knowledge in leakage management led to improvements in subsequent models such as BENCHLOSS and BENCHLOSSNZ in Australia and New Zealand (McKenzie & Seago 2003).

In a study in Zimbabwe, which was based on the night flow analysis of South Africa, SANFLOW, some factors were presented for estimating background leaks (Ndunguru & Hoko 2016). This model was developed by the South Africa Water Research Commission for determining the real water loss in a water supply zone with a specific demand using the recorded values of minimum night flow (MNF) as the main input (McKenzie 1999; Ndunguru & Hoko 2016). The model has good compatibility with the criteria of Iran Water and Wastewater Engineering Company (Guideline 556 of Iran MOE 2017). Besides, the employed approaches in these investigations, presenting experimental correlations for estimating leakage by the BABE method, were the subject of some studies (Amoatey *et al.* 2018).

It was emphasized that while the difference between the obtained results using various methods of background leakage estimation is insignificant, the MNF can be considerably affected by the legitimate night-time consumption (LNC) (Lee *et al.* 2005). Employing the MNF method has some uncertainties (Al-Washali *et al.* 2019). Some of the components of LNC are estimated, and the pre-specified patterns may not always present the right results. When the amount of leakage is obtained based on the MNF time, for acquiring the total daily leakage, the amount of leakage should be calculated during the day (García *et al.* 2008). The usage of experimental methods has been evaluated in the MNF analysis as it was used in the BABE method. For example, the MNF analysis has been examined in a network in Malaysia with parameters such as the number of customers, the network length, the weighted average of pipe age, and the mean network pressure (Alkasseh *et al.* 2013).

In 2013, Adlan *et al.* analyzed the MNF of the Prague-Malaysia water network using PrimeWorks and SPSS. The examination of the MNF variations was done using the one-way analysis of variance (ANOVA). The frequency of MNF occurrence was recorded every 15 minutes. The results indicate that in the 30 studied regions the MNF mostly took place between 02:15 and 04:15, while the minimum occurrence frequency of MNF was observed at 01:00 and 05:00 (Adlan *et al.* 2013).

In 2015, Taeho Choi *et al.* employed Bayesian inference and customer polls in order to determine the MNF for evaluating the efficiency of leakage management. Regions were categorized based on the variations of customers and the network condition. Finally, since the estimations were done successfully, it was concluded that it can be employed in the other regions as well (Choi *et al.* 2015).

Farah and Shahrour recognized the possibility of pipe burst in the water network of Lille Nord de France University, presenting the idea of real-time MNF analysis based on determining the flow thresholds. Thus, besides the reduction of the repair time, the NRW level was decreased by 36% (Farah & Shahrour 2017).

Besides, the comparison of the acquired results from the MNF and BABE methods and using them for determining the background leakage were suggested (Mutikanga 2012). The BABE and MNF methods were compared based on their capabilities, limitations, requirements, and precision in the previous researches (Taha *et al.* 2016, 2020).

It is considerably important to recognize the estimated parameters in the BABE and MNF methods (Amoatey *et al.* 2014). The night-time consumption of domestic customers is one of the influential parameters in the evaluation of LNC. Based on the climate, and cultural or social differences in each country, the domestic night-time consumption may be different in various regions; thus, in order to determine the real loss of the network with MNF analysis, employing suitable techniques for specifying the right domestic night-time consumption values in the studied region is essential (Norouzi *et al.* 2019). Different investigations have been performed in this field. In the early 1990s, some studies in the UK showed that the night-time consumption of domestic customers is determined using the active population in the night (6% of the total population) and the average consumption of each person during the night (10 lit/person/hr). Therefore, considering the occupants in each property in the investigated region, the night-time consumption of domestic customers was obtained as 1.7 lit/property/hr. The important point is estimating the LNC values based on the volume of the toilet flush tanks (UK Water Industry 1994; Amoatey *et al.* 2014; Norouzi *et al.* 2019). Table 1 presents some other investigations that were conducted for estimating the night-time consumption of customers.

The aforementioned reviews of the previous studies show that in the last two decades analyzing water loss and leakage with the BABE and MNF methods has been comprehensively investigated by many researchers. Most of the efforts were on improving the accuracy of the techniques and reducing their uncertainty. However, there are limited studies that examine the effectiveness of each influential parameter on the obtained results from these methods.

Table 1 | The investigations carried out to determine the night-time water consumption of domestic customers (Amoatey *et al.* 2014; Norouzi *et al.* 2019)

Examined region (year)	Considered conditions	Value
UK industries (1994)	Development of the region, population density, and people's behavioral habits	0.6 Lit/person/hr
South Africa (1999)	An active population of 6% during the MNF, and water usage in order of 10 lit/person/hr	1.7 Lit/household/hr 0.6 L/person/hr
Palestine, Ramallah (2004)	Development of the region, population density, people's behavioral habits, and the season of examination	0.2–0.5 Lit/s/km
UK (2001, 2008, 2012)	Unspecified	1.7 Lit/property/hr 7.4 Lit/non-household/hr
Canada, Ottawa (2007)	An active population of 6% during the MNF, 3 residents per connection, and a 13-lit toilet flush	2.34 Lit/connection/hr Non-domestic demand 1,200 Lit/hr
Austria (2009)	A population of 2,000–40,000 person in each DMA – without industrial consumption during the night	0.4 to 0.8 Lit/person/hr
USA, Tennessee (2010)	Rural customers – mainly for flushing the toilet	5.68 Lit/customer/hr
Iran, Khalazir village of Tehran (2011)	The MNF analysis for 6 months, during summer and autumn	2.15 Lit/person/hr
Australia (2012)	Toilet flushing – Leaking faucets	1.08 Lit/connection/hr
Germany, DVGW (2012)	A population of 2,000–40,000 person in each DMA – without industrial consumption during the night	0.6 Lit/person/hr
Canada (2012)	Unspecified	3 Lit/property/hr
Malaysia (2012)	Unspecified	5 Lit/property/hr
Uganda, Kampala (2012)	Examined during the MNF	3 Lit/property/hr
ASEAN region (2012)	3 persons in each household and 3% of the active population used toilets, bathroom, and faucets	0.45 Lit/person/hr 1.4 Lit/residential property/hr
Bangkok, Thailand (2013)	Examined during the MNF, in an isolated region with 2,000 customers, and without non-domestic usage	8.23 Lit/property/hr

One of the most important ways to increase the accuracy and make the results of these methods more realistic is to compare them in a system with specified conditions. Therefore, in order to increase the estimation accuracy in this research, by defining a case study, the analysis will be conducted and compared using these two techniques. Moreover, the impacts of important and effective parameters will be separately investigated in both of these methods. In the BABE method, two parameters including infrastructure condition and leakage exponent will be examined. Also, in the MNF technique, the influence of LNC of the customers and the leakage exponent on the obtained results will be evaluated and compared.

The selected region as the case study for this investigation has some characteristics that were not examined in the previous reports. One of them is being a rural region with tourist attractions and the other one is providing a water distribution with different pressure conditions to the customers in the zone. This is important because the distribution of water with various pressures affects the consumption pattern. It is worth noting that in the water supply systems with various pressures, the probability of burst and leakage is much greater, so these systems are major candidates for applying leakage analysis techniques. Furthermore, in order to improve the accuracy of the solution, the data will be collected every 10 minutes, and the evaluations will be based on these measurements.

MATERIALS AND METHODS

In this section, the condition of the studied system, equipment, measuring technique, collecting data, and the analytical methods will be explained.

The network of the case study

The examined network in this research is the water network of Gavankola village in Babol city in the north of Iran. The Mazandaran Province Rural Water and Wastewater Company is responsible for supplying and providing water for this village (Figure 1). This village has a temperate

Figure 1 | Location of Mazandaran and Babol.

climate and is a tourist attraction spot. Thus, visiting and water usages increase on weekends in this village.

In the water supply network of Gavankola, the water obtained from the underground well is chlorinated and pumped into the elevated water reservoir. Afterward, the water in the reservoir is distributed in the network by gravity. The elevation difference between the reservoir and the customer connection locations is very diverse, which leads to difficult operating conditions as well as low pressures for some customers during peak hours.

While in other parts of the region, not only there is not a low-pressure problem, but also they experience excess pressure in some hours of the day.

In many countries, users apply private tanks to reduce their vulnerability to water scarcity (De Marchis *et al.* 2011). Where water distribution is periodically supplied on an intermittent basis, users often modify their internal water system to introduce private tanks with pumps to collect as much water as possible – even if the available pressure is lower than the minimum required to have tank inflow (Puleo *et al.* 2014). Using a private pump, the storable volume and its ratio with the total consumption in one day is a very important factor (Mohammadzade Negharchi *et al.* 2016).

A pressure-driven model offers a more realistic representation of the influence on the network behavior of the private tanks during filling and emptying (Puleo *et al.* 2014).

As can be observed in the hydraulic model in Figure 2, in the indicated regions, most of the domestic customers employ water storage tanks for storing the water in the high pressure (or night) time.

Based on the field examination in Gavankola village, private tanks are mostly located in the basement and the water is distributed by house water pumps.

The pipes in the water network of this region were made of polyethylene, and the characteristics of the network pipes and the number of customers have been presented in Table 2. Moreover, the numbers of reported bursts in the distribution network and connections, and the usual time duration between the incident and repairing it in this village, have been tabulated in Table 3. These statistics were prepared in a one year period based on the reported pipe breaks and bursts, which were provided by Rural Water and Wastewater Company of Mazandaran.

Monitoring equipment and measurements

The data required in this study were collected on the basis of data measurement over a period of one month with frequency of data transmission every 10 minutes. The utilized ultrasonic flowmeter (SonixMeter SL300) was equipped with data loggers and it was installed on the inlet pipeline of the network (Soleyman.Co 2020). The flow velocity measurement was conducted by evaluating the time difference of the ultrasonic signals between the transit-time sensors. In this regard, after installing the clamp sensors on the pipe, an accurate portable ultrasonic flowmeter

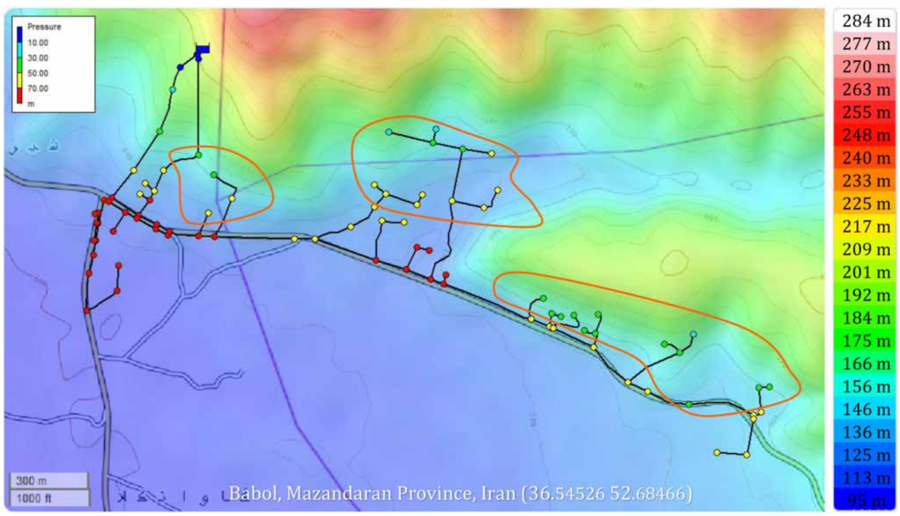


Figure 2 | The pressure values in the Gavankola village water supply network under normal consumption condition.

Table 2 | The characteristics of the network

Parameter	Values
Number of connections for domestic customers	290
Number of public connections	4
Number of commercial connections	4
The length of the network (km)	7.963
The network age (years)	3–20
The diameters of the pipes (mm)	32–125

Table 3 | The statistics of the reported pipe breaks and bursts in the village network

Parameter	Values
Number of bursts in the distribution network pipelines	47
Number of bursts in the connections service	31
The duration of bursts in the distribution network (hrs)	24
The duration of bursts in the connections service (hrs)	72

(pre-calibrated) was used to calibrate the flow rate. In addition, the pressure sensors record the pressure, while is connected to a data logger used to remote the recorded values. The data loggers, equipped with internal antenna, send gathered data via Short Message Service (SMS) at a user-defined period. The specifications of these flow and pressure measuring devices are presented in Tables 4 and 5, respectively.

Figure 3 shows the inlet flow rate of the network in 3 months. In order to present the data with lower fluctuations, the average flow rate was recorded every hour. The

Table 4 | Technical specifications of ultrasonic flowmeter (Soleyman.Co 2020)

Item	Value & Specifications
Measurement method	Ultrasonic measurement of flow velocity
Damping rate	6 (s)
Accuracy of reading	+/− 1.0% of measured range
Repeatability of reading	+/− 0.3%
Configurable pulse and relay output	Digital RS 232
Clamp & IP rating	On M2 (on encapsulated IP 68 sensors require no pipe cutting)
Wide operating temperature range	0 °C to 60 °C

Table 5 | Technical specifications of pressure transmitter (Rayan.Co 2020)

Item	Value and specifications
Response time	1 (s)
Rang of reading	0–32 (Bar)
Accuracy of reading	0.5% of full scale
Output	4–20 (mADC)
Wide operating temperature range	10 °C to 50 °C

mean flow rate during the weekdays has been illustrated in Figure 4. As can be observed, on the weekends (Thursday and Friday are the weekends in Iran) due to the presence of the tourists, Water consumption has increased. Overall, the average flow rate in the examined time period was calculated to be 4.2 Lit/s.

Water loss component assessment methods

Generally, the process of evaluating and determining the volume of leakage in the water supply network is done with four different methods (Taha *et al.* 2020):

- Top-Down approach (water balancing)
- Water and wastewater balancing
- Component analysis of leakage (the BABE method)
- Down-Top approach (the MNF method)

The balancing method is independent of network pressure; so, it is not considered in this study.

Component analysis of leakage (the BABE method)

The component analysis of leakage is a method in which the existing leakage volume in the network is modeled based on the leakage type and the time of occurrence. In fact, with this method, the effective parameters in the leakage are analyzed using the repair statistics. In the BABE analysis, it is assumed that the annual number of repairs is the same number of reported pipe breaks or bursts. These leaks are categorized into different groups with various flow rates. With a logical evaluation of the time duration for each leakage and burst, the annual water loss for each component can be calculated. If the exact initial data were not available, the available values in the standards can be utilized for the

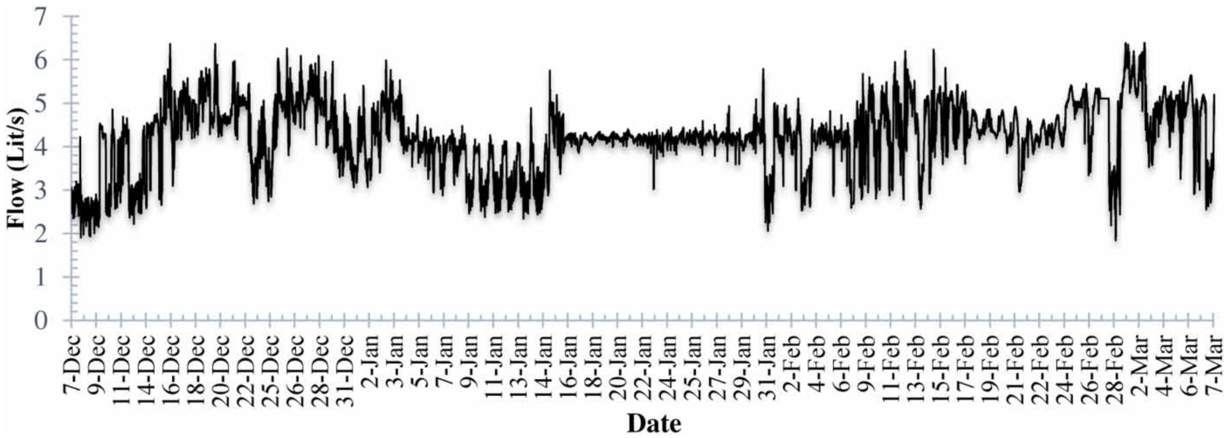


Figure 3 | The inlet flow rate of the village distribution network in a time period of 3 months.

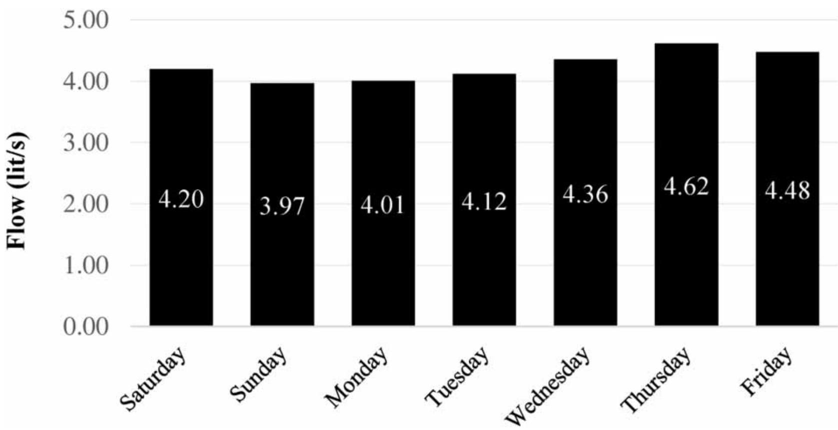


Figure 4 | The average of inlet flow rate in the village network on different days of a week.

initial estimation (Baader *et al.* 2011). The reported and unreported bursts in the pipelines and connections are calculated using Equations (1) and (2) (Guideline 556 of Iran MOE 2017):

$$Q_{LP} = FQ_{leak}\left(\frac{P_{av}}{50}\right)^{N} Lt \tag{1}$$

$$Q_{SP} = FQ_{leak}\left(\frac{P_{av}}{50}\right)^{N} nt \tag{2}$$

Q_{LP} and Q_{SP} show the leakage due to the burst of pipelines and the leaks due to burst of connections, respectively. F indicates the number of bursts in the network pipeline in km/year, and for the connections, it indicates the number of bursts per 1,000 connections/year (Table 3), Q_{Leak} is the leakage flow rate due to the bursts in the pipelines in L/km/hr, and in the connections in L/connection/hr (in the pressure of 50 meters, as shown in Table 6, P_{av} is the mean network pressure in meters, n is the number of connection divided by 1,000 (Table 3), L is the length of the main network line in km, and, finally, N and T indicate the leakage exponent in the network, and the time interval between the pipe break and repairing it in hours, respectively (Table 3).

The leakage flow rate due to reported and unreported bursts in the distribution network and connections are based on the existing standards in Table 6. Considering that in order to raise the calculation accuracy the unreported pipe breaks and burst in the distribution network

Table 6 | The recommended values for calculating the water loss due to bursts (Guideline 556 of Iran MOE 2017)

Components of the network	Reported bursts: Frequency of occurrence	Reported bursts: Leakage flow rate (m^3/hr)	Unreported bursts: Frequency of occurrence	Unreported bursts: Leakage flow rate (m^3/hr)
Distribution network	(0.15) km/year	12.0	(0.008) km/year	6.0
Connections service	(2.5) per 1,000 connection/year	1.6	(0.825) per 1,000 connection/year	1.6

and the connections should be estimated; the available standards and assumptions in Table 7 can be employed.

For calculating the leakage volume, the leakage exponent (N) in the network is needed. Due to the lack of proper conditions and the inability to use the practical method, the N value was selected based on the information of the previous studies. These values were presented in several studies (Alkasseh *et al.* 2013; Amoatey *et al.* 2014, 2018; Ndunguru & Hoko 2016; Taha *et al.* 2016). Similar to one of the previous studies (Ndunguru & Hoko 2016), in this research, the value of $N = 0.5$ was applied for determining the reported and unreported pipe breaks and bursts. In order to calculate the background leaks, Equations (3) and (4) were employed (Guideline 556 of Iran MOE 2017):

$$Q_{BLP} = Q_{leak}\left(\frac{P_{av}}{50}\right)^{N} \tag{3}$$

$$Q_{BSP} = Q_{leak}\left(\frac{P_{av}}{50}\right)^{N} \tag{4}$$

In these equations, Q_{BLP}, and Q_{BSP} are background leaks from mains and connections, respectively. Also, as can be observed in Table 8, Q_{Leak} has been presented based on the network infrastructure conditions: bad, medium, and good.

Table 7 | The base information for estimating the unreported bursts (Guideline 556 of Iran MOE 2017)

Components of the network	Number of unreported bursts	The flow rate of unreported bursts
Distribution network	5–10% of the reported bursts	Q/2 of the reported burst
Connections service	30–35% of the reported bursts	Equivalent to the Q of reported bursts

Table 8 | The recommended values for the background leaks in the pressure of 50 meters (based on the infrastructure conditions of the network)

Background leakages	A previous study (Ndunguru & Hoko 2016) A	Guideline (Guideline 556 of Iran MOE 2017) Bad B	Medium C	Good D
Background leakage from mains (Lit/km.hr)	40	60	40	20
Background leakage from connections (Lit/conn.hr)	3	4.5	3	1.5
Background leakage from properties (Lit/conn.hr)	1	–	–	–
The leakage exponent of the background leak	1.5	–	–	–

Minimum night flow analysis technique

The minimum measured value of flow rate in a District Metered Area (DMA), during a 24-hour period and in the time period of minimum customer demand, is known as the minimum night flow (Al-Washali *et al.* 2019). Due to the reduction in consumption, MNF usually happens in the early hours of the morning. In this method, with considering the LNC of a DMA, and with subtracting it from the MNF value, the amount of mean night leakage is obtained (Baader *et al.* 2011). After estimating the real water loss, the apparent loss can be acquired by subtracting the real water loss from the total water loss in the network (Taha *et al.* 2016). The components of MNF have been presented in Table 9 (Ndunguru & Hoko 2016).

The MNF technique is suitable for the systems with a continuous supply. The share of legitimate consumption

Table 9 | Components of the night flow (McKenzie 1999; Ndunguru & Hoko 2016)

Components of night flow	Composition	Abbreviation	Unit	Method of determination
(EMNF)	Domestic users	Q_{dom}	(Lit/hr)	Estimated
	Small non-domestic users	$Q_{bulk,\ small}$	(Lit/hr)	Estimated
	Large non-domestic users	$Q_{bulk,\ large}$	(Lit/hr)	Measured
Transfer	Transfer of water to neighboring zones	Q_{trans}	(Lit/hr)	Measured
ENF	Background losses and burst pipes	Q_{loss}	(Lit/hr)	Calculated

and losses is determined using Equation (5) Baader *et al.* (2011):

$$Q_{in} = Q_{dom} + Q_{bulk} + Q_{trans} + Q_{loss} \tag{5}$$

In this equation, Q_{in} is the system input, Q_{dom} is the domestic night-time consumption, Q_{bulk} is the small and large non-domestic night-time consumptions, Q_{trans} is for the transfer of water to neighboring zones, and Q_{loss} is for the water loss. The legitimate consumption includes the domestic night-time consumption (mostly for flushing toilets), Q_{dom}, and non-domestic night-time consumption (administrative, industrial, commercial or agricultural consumers), Q_{bulk}. Legitimate consumption can be a large portion of the MNF. A field examination can estimate or determine domestic night-time consumption; however, it is important to specify the night-time consumption of major consumers. The amount of water transfer to neighboring zones, Q_{trans}, should be either evaluated or stopped during the evaluation of MNF (Baader *et al.* 2011; Taha *et al.* 2020).

In order to obtain the daily water loss in the studied area, the ratio of district night and day pressures should be considered when calculating the Night to Day Factor (NDF). The pressure profile in the Average Zone Point (AZP) should be measured, and the leakage exponent of the system (N), should be determined for calculating the NDF. The amount of daily water loss, $Q_{loss,d}$, can be acquired using these two equations (Baader *et al.* 2011; Taha *et al.* 2020):

$$Q_{loss,d} = NDF \times Q_{loss} \tag{6}$$

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

In these equations, $Q_{loss,d}$ indicates the daily water loss in m^3/day, Q_{loss} is the mean night-time consumption in m^3/hr, P_i is the 24-hour mean pressure, and the P_{MNF} shows the mean pressure during the minimum night-time consumption condition (Baader *et al.* 2011; Taha *et al.* 2020).

The pipes of this network were made of viscoelastic material (polyethylene) (Evangelista *et al.* 2015). Due to the hysteretic effect for leakages in a viscoelastic pipe, numerical tests confirm the existence of an exponential law to the decay and leakage due to high pressure in the plastic pipe (Brunone *et al.* 2015).

Field studies have shown that the sensitivity of the leakage rate to total head (N) can be significantly larger than 0.5 and typically varies between 0.5 and 2.79, with a mean value of 1.15. The value of the exponent N depends on leak type and pipe material behavior (De Marchis *et al.* 2016). The results presented in Schwaller & van Zyl 2015 show that the network's displayed leakage exponents are between 0.46 and 1.67, with the vast majority of values lying between 0.5 and 1.5.

Assumptions

The assumptions used for the preferred models are as follows:

1. The leakage exponent for the viscoelastic system increased almost from 0.89 at a mean pressure of 20 m, to 1.23 at a mean pressure of 65 m (Schwaller & van Zyl 2015). Therefore, considering that the average pressure in this research is 55.3 m, the value of N is considered to be 1.16.
2. Avoidable losses (bursts) are typically due to leaks with a constant cross area, so they are proportional to the mean night-time consumption of the region, with an exponent of 0.5 (Baader *et al.* 2011; Ndunguru & Hoko 2016).

3. The mean night-time consumption of customers (considering the constant volume of the private tanks) is independent of pressure in the district.
4. Based on the field examination in Gavankola village, 40% of domestic customers have private water tanks with a volume of 500 lit, and it is assumed that 80% of the volume of these private tanks is filled with water in the night.
5. In calibration, the Hazen–Williams coefficients of the pipelines are considered 85 (by averaging the presented values in a previous study (Cheung *et al.* 2010)).

RESULTS AND DISCUSSION

Based on the measurements and according to Figure 4, the average consumption is close to the consumption on Wednesday, thus in order to consider an average condition, the data of Wednesday is used for the analysis. The minimum and maximum measured flow rates in the day are 3.07 and 5.4 lit/s, respectively. Also, the minimum, maximum and average pressures are 44.2, 61.9, and 55.3 m, respectively.

The results of BABE method

In this research, the results were carried out in two conditions of medium and bad (Table 7). Also, for evaluating the effects of the leakage exponent, according to the guideline (Guideline 556 of Iran MOE 2017), a value of $N = 1.15$ was considered in Table 10.

As was stated before, the results of water loss components in the BABE method are based on the initial estimations and there may be some errors. With the conducted analysis by South Africa's model, SANFLOW (Ndunguru & Hoko 2016) and the recommended model by Iran Water and Wastewater Company (Guideline 556 of Iran MOE 2017), the real water losses were obtained as 1.02 and 1.21 lit/s, respectively. The highest leakage values were for the reported bursts (32%), and the background leaks from connections (28%).

Evaluating the influence of the leakage exponent shows that this value has less influence in the analysis with the BABE method (Table 10). Therefore, by changing the exponent value from $N = 0.5$ to $N = 1.5$, the difference in the results is only 10%. Consequently, for increasing the accuracy of the estimations in the BABE method, it is recommended to focus on the evaluation of the background leaks from the connections and the mean leakage from the burst in each DMA.

Table 10 | The results of water loss components based on the BABE method

	Leak value (Lit/s)		
The leakage type	**Case A & $N = 1.5$**	**Case B & $N = 1.5$**	**Case B & $N = 1.15$**
Reported bursts	0.45	0.45	0.48
Unreported bursts	0.02	0.02	0.02
Background leaks from bursts	0.10	0.15	0.15
Reported connection bursts	0.12	0.12	0.13
Unreported connection bursts	0.04	0.04	0.04
Background leaks from connections	0.29	0.43	0.42
Real water loss	1.02	1.21	1.23
Reported leaks from properties	0.00	0.00	0.00
Unreported leaks from properties	0.14	0.14	0.15
Background leaks from properties	0.10	0.10	0.09
Total leakage	1.25	1.45	1.47

The results of the MNF method

After reviewing related studies on the determination of night-time water consumption of domestic customers in Table 1, the following can be concluded:

- Due to the presence of livestock and poultry in the rural regions, and also different social habits of the customers in these areas, the water consumption in these rural regions is higher compared to the urban regions.
- The night-time consumption of domestic customers in the areas with tourists (like Bangkok) is higher than the areas without tourists because during the night people are more active in these areas.

- The night-time consumption of customers in Islamic countries (such as Iran and Malaysia) is higher than the non-Islamic countries (like the UK, Germany, or Australia).

Considering the assumptions listed above, and the above mentioned parameters, which are all influential in the consumption of Gavankola village, the total stored volume in the private tanks of customers in the night was calculated. The storage process is performed in 7 hours and 10 minutes (based on the pressure measurement and pattern depicted in Figure 5), the consumption is obtained as 21.75 lit/hr per customer.

$$\text{The total night-time volume} = (40\% \times 290) \times (80\% \times 500 Lit) = 46400\, Lit$$

$$Q_{dom} = \frac{46400\,(Lit)}{298(\text{household}) \times 7.17(hr)} = 21.75\ \text{Lit/household/hr}$$

Thus, contrary to the suggestion made in the previous research (UK Water Industry 1994), the acquired LNC is significantly larger than the 1.7 lit/connection/hr (by 14 times). This is mainly due to the fact that the consumption of the customers for filling the domestic storage tanks with water during the night is considerable. This difference was also observed in the previous research, in which the LNC of two regions in Ottawa was also found to be larger (3.5–8 times in the first region, and 5–9 times in the second region). It was stated that the reason for this difference in the LNC of the regions was the usage of water purification devices by customers (Norouzi *et al.* 2019).

Moreover, according to the summary presented in Table 1, the night-time consumption of non-domestic customers is obtained. In this network, there is no water transfer to/from neighboring zones, therefore:

$$Q_{bulk} = \frac{7.4 \times 8}{298} = 0.198\ \text{Lit/non}-\text{household/hr}$$

$$Q_{trans} = 0$$

The obtained results from the MNF analysis of Gavankola village, including the changes in the pressure, flow rate and leaks during different hours, are presented in Figure 5. According to Figure 5, the LNC of customers is 1.81 lit/s. This flow rate is estimated for filling the domestic water storage of the customers who do not have appropriate water pressure and flow rate during the peak and low-pressure times. Also, the leakage from the network varies with time and has an average of 1.105 lit/s. According to Figure 5, the analysis performed every 10 minutes indicates that in this network the MNF occurs at 00:00 and 05:00, which is due to the customs and culture of the customers in this village. Considering that the leakage calculation analyses are performed based on estimations, errors are inevitable. Figure 6 shows the influence of LNC and leakage exponent (N) on the estimated leakage in the water network of Gavankola. According to Figure 6, changing the N value as much as 0.1 alters the estimated leakage by only 1%,

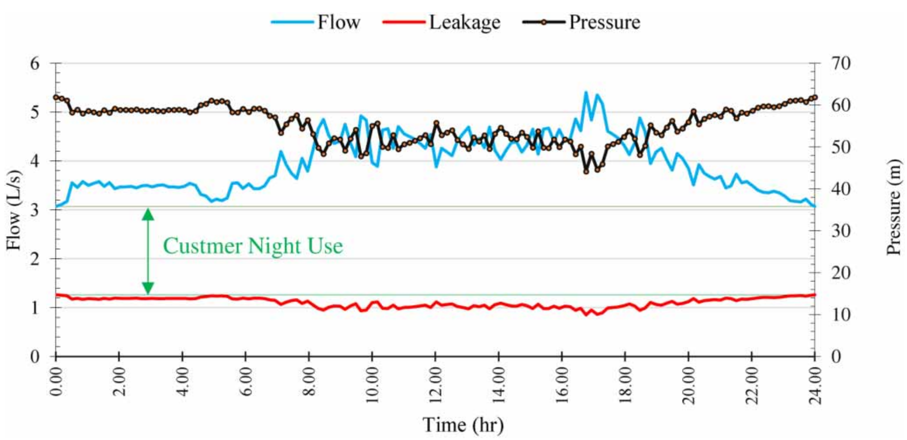


Figure 5 | The changes in the flow (indicating MNF), pressure, and leakage in Gavankola village, Iran, throughout the day.

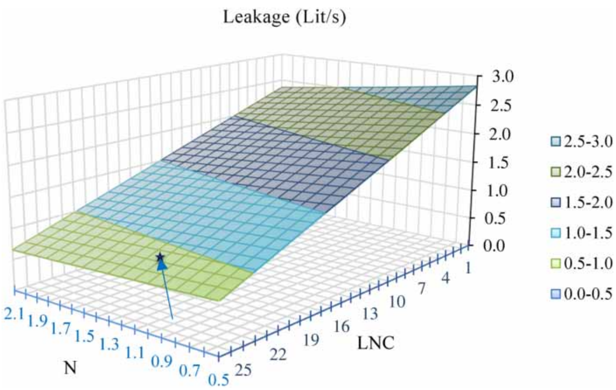


Figure 6 | The influence of LNC and leakage exponent on the estimated leakage in the water network of Gavankola.

while changing the LNC by one step alters the calculated leakage by 14%.

The summary of the measured, estimated, and calculated parameters using the BABE and MNF methods have been presented in Table 11.

CONCLUSIONS

Given the importance of leakage management nowadays, different methods have been presented for estimating water loss. In this study, the results of BABE and MNF methods for Gavankla village network (in Iran), with 298 connections, were evaluated and compared. It is worth noting that the NRW at the time of conducting this study was 47%, which is higher than the recommended value of the World Bank (23%). Also, Islamic culture, living in rural conditions, and the tourist attraction are the influencing factors in the consumption pattern, with few studies in this field. In the region selected for the case study, there are all the features mentioned. Therefore, effective loss management strategies are essential to improve the performance of this network. Pressure and flow rate data were measured over a period of one month with frequency of data transmitted every 10 minutes. This will increase the number of mean pressure data and increase the accuracy of the MNF method. Among the more important results obtained in this study, the following may be mentioned:

- The mean inlet water flow rate in the network was 4.2 lit/s; based on the BABE analysis for the bad and medium infrastructure conditions, the leakage is calculated as 1.45 and 1.25 lit/s, respectively, while with the MNF method and by considering an LNC of 1.81, the average leakage was obtained as 1.105 lit/s. Therefore, using the MNF and BABE methods, the average of real water loss in the studied region was calculated as 28 and 37%, respectively.
- According to the results of the BABE method, the highest leakage values were related to the reported bursts, and the background leaks from connections.
- In this rural region, according to hydraulic and consumption conditions, the highest frequency of MNF occurrence was observed at 00:00 and 05:00.
- Comparing the effects of LNC and leakage exponent (N) indicates the higher importance of the LNC parameter in

Table 11 | Summary of parameters used in the leakage estimation

Network parameters	Symbol	Units	Value	Remarks
Legitimate night-time consumption	LNC	Lit/person/hr	21.84	Estimated for network
Total customer night use	$N_s(Q_{dom} + Q_{bulk})$	Lit/hr	7,019	Measured and estimated in Assumptions section & Table 1
Minimum night flow	Q_{loss}	Lit/hr	4,033	Obtained MNF logging
Night-day factor	NDF	–	20.25	Measured and computed in Figure 5
Total MNF leakage	$Q_{loss,d}$	m^3/day	95,514	Measured and estimated parameters
Total BABE-1 leakage	$Q_{loss,d,BABE1}$	m^3/day	108,000	Result computed in Table 10
Total BABE-2 leakage	$Q_{loss,d,BABE2}$	m^3/day	125,280	Result computed in Table 10
Daily volume supplied	Q_{day}	m^3/day	341,400	Measured MNF curve
Real water loss	RL	%	28	Measured MNF method
Non-revenue water	NRW	%	47	Measured and company report

the calculation of the leakage, because in this network some customers use a water storage tank. It is noteworthy that in previous studies the value of LNC was 1.35 to 15.3, while in this study the value of LNC is obtained as 21.84.

- Comparison between the results of the BABE method and the MNF method indicates that the Gavankola village WDN has a medium condition infrastructure.
- In order to determine the real loss and leakage of the network with the MNF analysis, employing suitable techniques for specifying the right domestic night-time consumption values is essential. Therefore, for future work, research on methods for obtaining the LNC parameter is suggested.

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DATA AVAILABILITY STATEMENT

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

REFERENCES

Adlan, M. N., Alkasseh, J., Abustan, I. & Hanif, A. B. M. 2013 Identifying the appropriate time band to determine the minimum night flow: a case study in Kinta Valley, Malaysia. *Water Science and Technology: Water Supply* **13**, 328–336.

Alkasseh, J. M., Adlan, M. N., Abustan, I., Aziz, H. A. & Hanif, A. B. M. 2013 Applying minimum night flow to estimate water loss using statistical modeling: a case study in Kinta Valley, Malaysia. *Water Resources Management* **27**, 1439–1455.

Al-Washali, T., Sharma, S., Al-Nozaily, F., Haidera, M. & Kennedy, M. 2019 Modelling the leakage rate and reduction using minimum night flow analysis in an intermittent supply system. *Water* **11**, 48.

Amoatey, P., Minke, R. & Steinmetz, H. 2014 Leakage estimation in water networks based on two categories of night-time users: a case study of a developing country network. *Water Science and Technology: Water Supply* **14**, 329–336.

Amoatey, P., Minke, R. & Steinmetz, H. 2018 Leakage estimation in developing country water networks based on water balance, minimum night flow and component analysis methods. *Water Practice and Technology* **13**, 96–105.

Baader, J., Fallis, P., Hübschen, K., Klingel, P., Knobloch, A., Laures, C., Oertlé, E., Trujillo, R. & Ziegler, D. 2011 *Guidelines for Water Loss Reduction–A Focus on Pressure Management*. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, Eschborn.

Brunone, B., Meniconi, S., Capponi, C. & Ferrante, M. 2015 Leak-induced pressure decay during transients in viscoelastic pipes. Preliminary results. *Procedia Engineering* **119**, 243–252.

Cheung, P. B., Girol, G. V., Abe, N. & Propato, M. 2010 Night flow analysis and modeling for leakage estimation in a water distribution system. Conference on Integrating Water Systems (CCWI). Taylor & Francis Group, London, pp. 509–513.

Choi, T., Hong, M., Kim, J. & Koo, J. 2015 Efficient minimum night flow analysis using Bayesian inference. *Journal of Water Supply: Research and Technology – AQUA* **64**, 10–18.

Colombo, A. F. & Karney, B. W. 2002 Energy and costs of leaky pipes: toward comprehensive picture. *Journal of Water Resources Planning and Management* **128**, 441–450.

De Marchis, M., Fontanazza, C., Freni, G., Loggia, G. L., Napoli, E. & Notaro, V. 2011 Analysis of the impact of intermittent distribution by modelling the network-filling process. *Journal of Hydroinformatics* **13**, 358–373.

De Marchis, M., Fontanazza, C. M., Freni, G., Notaro, V. & Puleo, V. 2016 Experimental evidence of leaks in elastic pipes. *Water Resources Management* **30**, 2005–2019.

Evangelista, S., Leopardi, A., Pignatelli, R. & de Marinis, G. 2015 Hydraulic transients in viscoelastic branched pipelines. *Journal of Hydraulic Engineering* **141**, 04015016.

Farah, E. & Shahrour, I. 2017 Leakage detection using smart water system: combination of water balance and automated minimum night flow. *Water Resources Management* **31**, 4821–4833.

García, V. J., Cabrera, E. & Cabrera Jr, E. 2008 The minimum night flow method revisited. *Water Distribution Systems Analysis Symposium* **2008**, 1–18.

Guideline 556 of Iran MOE 2017 Guideline for Determining Effective Parameters on Unaccounted for Water (UFW) and Water Losses Reduction Schemes; Code 556. Ministry of Energy, Water Industry of Iran. Confirmation Group: Water and Wastewater Expert Committee for Preparation of Technical Standards and Standards, University of Tehran Water Institute, in Persian, pp. 1-175.

Lambert, A. & Morrison, J. 1996 Recent developments in application of 'bursts and background estimates' concepts for leakage management. *Water and Environment Journal* **10**, 100–104.

Lee, H., Chung, S., Yu, M., Koo, J., Hyun, I. & Lee, H. 2005 Applicable background minimum night flow for leakage management of small district metered areas in Korea. *Water Science and Technology: Water Supply* **5**, 181–188.

McKenzie, R. 1999 *SANFLOW User Guide: South Africa Water Research Commission*, WRC Report No. TT 109/99. Water Research Commission, Pretoria, South Africa.

McKenzie, R. & Seago, C. 2003 Component based analysis for management of leakage in potable water supply systems. In *Australian Water Association Annual Conference*.

Mohammadzade Negharchi, S., Shafaghat, R., Najafi, A. & Babazade, D. 2016 Evaluation of methods for reducing the total cost in rural water pumping stations in Iran: a case study. *Journal of Water Supply: Research and Technology – AQUA* **65**, 277–293.

Mutikanga, H. E. 2012 Water loss management: tools and methods for developing countries. IHE Delft Institute for Water Education, Delft, The Netherlands.

Ndunguru, M. G. & Hoko, Z. 2016 Assessment of water loss in Harare, Zimbabwe. *Journal of Water, Sanitation and Hygiene for Development* **6**, 519–533.

Norouzi, J., Jalili Ghazizadeh, m. & Moslehi, I. 2019 A review of previous studies in determining the night water consumption of household customer (in Persian). In: *Second National Conference on Water Consumption Management, Loss Reduction & Reuse* (M. Tabesh, ed.). University of Tehran, Tehran, Iran, pp. 1–9.

Puleo, V., Fontanazza, C. M., Notaro, V., De Marchis, M., Freni, G. & La Loggia, G. 2014 Pumps as turbines (PATs) in water distribution networks affected by intermittent service. *Journal of Hydroinformatics* **16**, 259–271.

Rayan.Co 2020 Sepehr Jahangir Rayan Electronic Company, Mazandaran Science and Technology Park, see http://en.mstp.ir/Co-Details.aspx?ID=28 (accessed 1 March 2020).

Schwaller, J. & van Zyl, J. v. 2015 Modeling the pressure-leakage response of water distribution systems based on individual leak behavior. *Journal of Hydraulic Engineering* **141**, 04014089.

Soleyman.Co 2020 See also http://soleymantech.com (accessed 1 March 2020).

Taha, A.-W., Sharma, S. & Kennedy, M. 2016 Methods of assessment of water losses in water supply systems: a review. *Water Resources Management* **30**, 4985–5001.

Taha, A.-W., Sharma, S., Lupoja, R., Fadhl, A.-N., Haidera, M. & Kennedy, M. 2020 Assessment of water losses in distribution networks: methods, applications, uncertainties, and implications in intermittent supply. *Resources, Conservation and Recycling* **152**, 104515.

UK Water Industry 1994 *Managing Leakage Report E: Interpreting Measured Night Flows*. WRc plc/Water Services Association/Water Companies Association, Swindon, UK.

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