Component analysis for optimal leakage management in Madaba, Jordan

Hassan Aboelnga, Motasem Saidan, Radwan Al-Weshah, Michael Sturm, Lars Ribbe and Franz-Bernd Frechen

ABSTRACT

Non-revenue water (NRW) is a major challenge for urban water security in Jordan. Quantifying leakage and pinpointing the location of leaks are difficult tasks in intermittent supply systems. This study aims to provide a structured analysis to determine the volume of leakage and its components in Madaba's water distribution network. The study also offers recommendations to reduce the physical losses as an important component of water losses through an infrastructure, repair, economic, awareness and pressure (IREAP) framework as a way of systematically engaging the NRW challenge in Jordan. The real loss sub-components were analysed using Burst and Background Estimates (BABE), and field records of the failures in the network. The potential impact of interventions to reduce losses were measured for efficiency/efficacy by analysing pressure management, chronic leakage detection surveys and response time minimization. The findings showed that Madaba's NRW amounted to 3.5 million m^3 in 2014, corresponding to a loss of 2.8 million USD to the utility, of which 1.7 million USD is the cost of real losses. The reported failures in Madaba accounted for 37.2% of the total volume of real losses which can be improved by enhancing response polices and asset management, while the unreported failures constituted 26.6 and 36.20%, respectively, which could be reduced by pressure management and active leakage control.

Key words | apparent water losses, non-revenue water, real water losses, water balance, water system

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INTRODUCTION

Non-revenue water (NRW) is considered an important and omnipresent topic for urban water security with emerging challenges due to water scarcity and climate change (Brears 2017). From an economic point of view, it is essential to preserve this resource by reducing water losses. NRW not only represents an economic loss for water utilities, it also represents a wasted process for treating, pumping and distributing water to the end user, which results in an adverse impact on the safety of drinking water (Colombo & Karney 2005).

NRW is a major economic loss because it means that the monetary investment of treating water is also lost when the water does not reach subscribers. The same is valid for the energy that is, for example, invested in pressurizing water supplies to deliver water to the connected subscribers through the network (Kanakoudis & Muhammetoglu 2013).

It was estimated that the cost of water losses worldwide total US$14 billion annually (Kingdom *et al.* 2006). By identifying the causes of NRW and addressing all NRW components these highly valuable resources (water and energy) can be saved while investments and expenses are reduced. Ultimately, the necessary changes need to be addressed critically by utility managers of all related fields: from finance and administration to production and customer service (Farley 2008).

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Environmental scarcity, which is defined as the declining availability of renewable natural resources, is affected by climate variations which challenge the general availability of water. Environmental scarcity can be caused by the degradation renewable resources by natural processes and/or by an uneven distribution of resources leading to a deficit which can be exacerbated by population growth for example (Homrt-Dixon 1999). In Jordan, both factors are at play.

Located in a semi-arid to arid region with an annual rainfall of less than 200 mm over 92% of the land, Jordan's annual renewable resources of less than 100 m^3/capita are far below the global threshold of severe water scarcity of 500 m^3/capita. The country was ranked fourth among the world's most water-scarce countries in 2015 (Saidan *et al.* 2015), and currently it is ranked second in the world in water scarcity (Al-Awad *et al.* 2018; Saidan *et al.* 2018). Rapid population growth, climate change (Al-Weshah *et al.* 2016), and a massive influx of refugees, caused by the numerous and severe conflicts in the neighboring countries, were major stressors to Jordan's water share per capita and international ranking (Al-Hamamre *et al.* 2017; Saidan *et al.* 2017a, 2017b; Alrabie & Saidan 2018; Hindiyeh *et al.* 2018).

Population and economic growth are putting pressure on water utilities (Thompson *et al.* 2001). Water utilities in Jordan have been struggling to cope with the increasing deficits – meeting water demand with renewable supplies – which is exacerbated by the persistently high levels of NRW (Jordan's Water Strategy 2008).

Because of water shortage, water supply is distributed through intermittent supply schemes wherein households receive water only once or twice a week. Households are obliged to invest in roof storage tanks with 2–4 m^3 capacity and to purchase extra water from private vendors in order to meet their demand. The water utilities are confined to a kind of permanent crisis management, which prevents them from meeting customers' satisfaction and from developing and applying a structured NRW management strategy (Rosenberg *et al.* 2008).

Moreover, intermittent water supply poses a great challenge to quantify and manage leakages in the distribution network (Charalambous & Laspidou 2017). Despite many measures, NRW throughout Jordan has not been reduced significantly, still reaching 40–60% of the system input volume for most of the governorates, especially Madaba where 60% was accounted for as NRW in water supplies in 2013, corresponding to a loss of about 6 million m^3 (MWI 2013a, 2013b, 2013c; Miyahuna Madaba 2014).

Water utilities in Jordan have been facing many challenges for quantifying real (physical water losses in a distribution system) and apparent (non-physical losses that might be attributed to inaccuracies in metering, billing and repairs) losses due to the complexity of the network where supply is intermittent and minimum night flows measurements cannot be conducted (MWI 2013a, 2013b, 2013c, 2014). The study applies a component analysis to provide a structured assessment of the water loss components in the entire water supply system from the source to the end consumer.

A high level of NRW is an indicator of the water utility operational deficiency (Kingdom *et al.* 2006). The water utility in Madaba has been struggling to recover the operational and maintenance costs due to high levels of NRW, whether from physical losses through leakage in pipes or the apparent losses (Miyahuna Annual Report 2014). However, using the NRW indicator as a percentage is misleading and not meaningful for assessing the performance of leakage management (Liemberger 2002).

The objective of the present study is to identify the root causes of leakage in Madaba's intermittent water supply and to provide pragmatic interventions to reduce the real losses, which contributes to the level of NRW.

METHODS

Study area

Madaba Governorate lies in the middle of Jordan and is situated 35 km southwest of Amman. It has an area of about 1,000 km^2 and a population of 178,000 inhabitants (DOS 2016). The location map of the study area is shown in Figure 1.

Madaba Governorate is divided into two directorates: Madaba directorate being 498 km^2 and Deeban directorate being 543 km^2. The length of the water supply distribution system is 1,000 km from the source at Heedan wells to the customers meter, with an average pressure of 6 bars in the distribution network. According

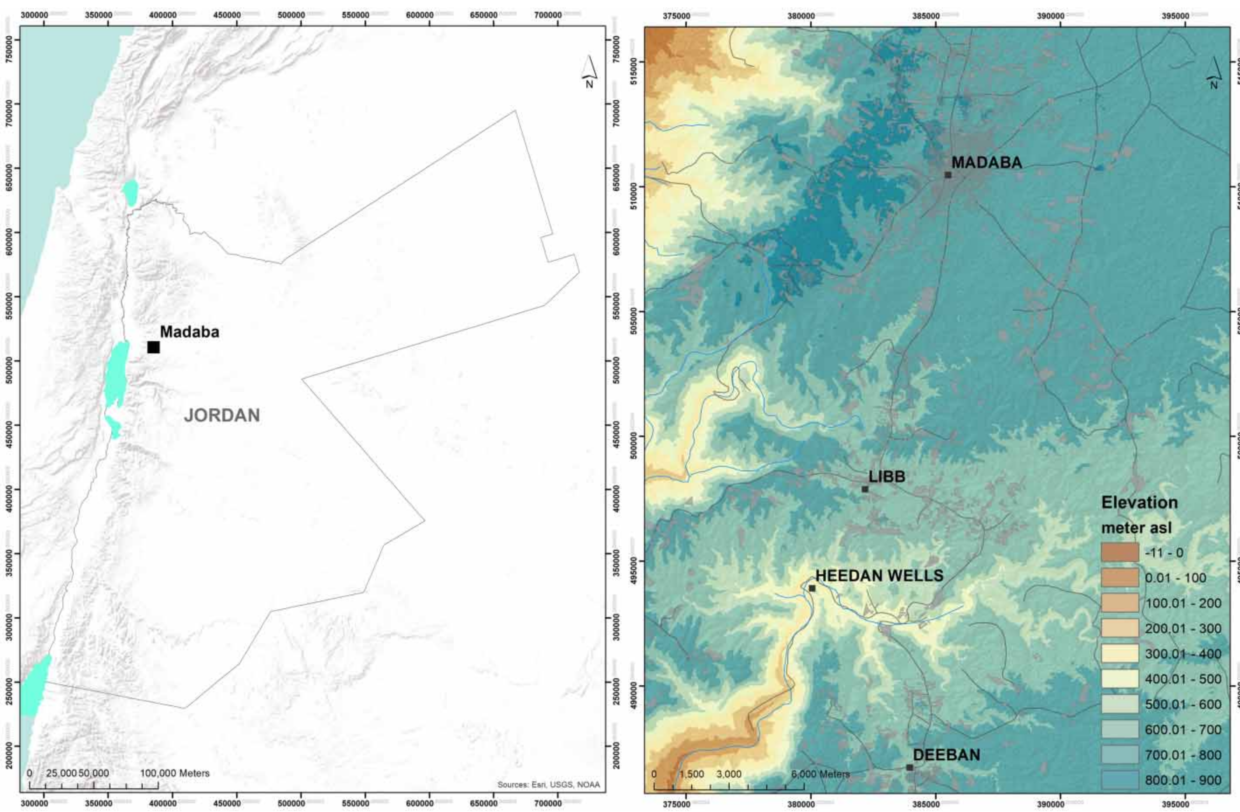

Figure 1 | Study area: Madaba city.

to the pressure measurement campaign, which was carried out to identify high pressure areas in Madaba town, the average pressure was about 6 bars in most of the network. While the highest pressure was 20 bars in the northern part of Madaba town, the lowest average pressure was 4.5 bars in the refugee camp area. Figure 2 shows a schematic of the water supply system in Madaba, Jordan.

Residential water subscribers represent 93% of the total subscribers and they consumed 88% of water sold with an average sales price of 0.575 JOD per 1 m^3 (0.81 USD). The numbers of Madaba subscribers are rising by about 5.5% each year. In 2016, Madaba directorate had 25,335 water subscribers while Deeban had 5857. Water consumption for both directorates amounted to about 5.0 million m^3 per year. The highest density of subscribers is in Madaba town with approximately 12,998 subscribers. As shown in Figure 2, Heedan wells represent the main sources for water supply of Madaba Governorate with a capacity of 2,100 m^3/hr. About 9 million m^3 every year was supplied to the whole governorate through the main transmission lines of Wala–Libb pumping stations.

Component analysis of water loss

The International Water Approach (IWA) water balance summarizes the components and provides accountability of system components' input and output. However, the reliability of the assessment of water balance accounting as a top-down approach depends heavily on the accuracy of the data. The disadvantages of calculating water loss in this way are as follows (Farley & Trow 2003):

- the water balance does not provide a clear indication of the real losses and how they are affected by the utility's strategy;
- the annual water balance does not provide an early warning framework to unreported leakage;
- there are often systematic errors in bulk metering.

Due to these reasons, a bottom-up approach can be used to estimate the water loss components through an

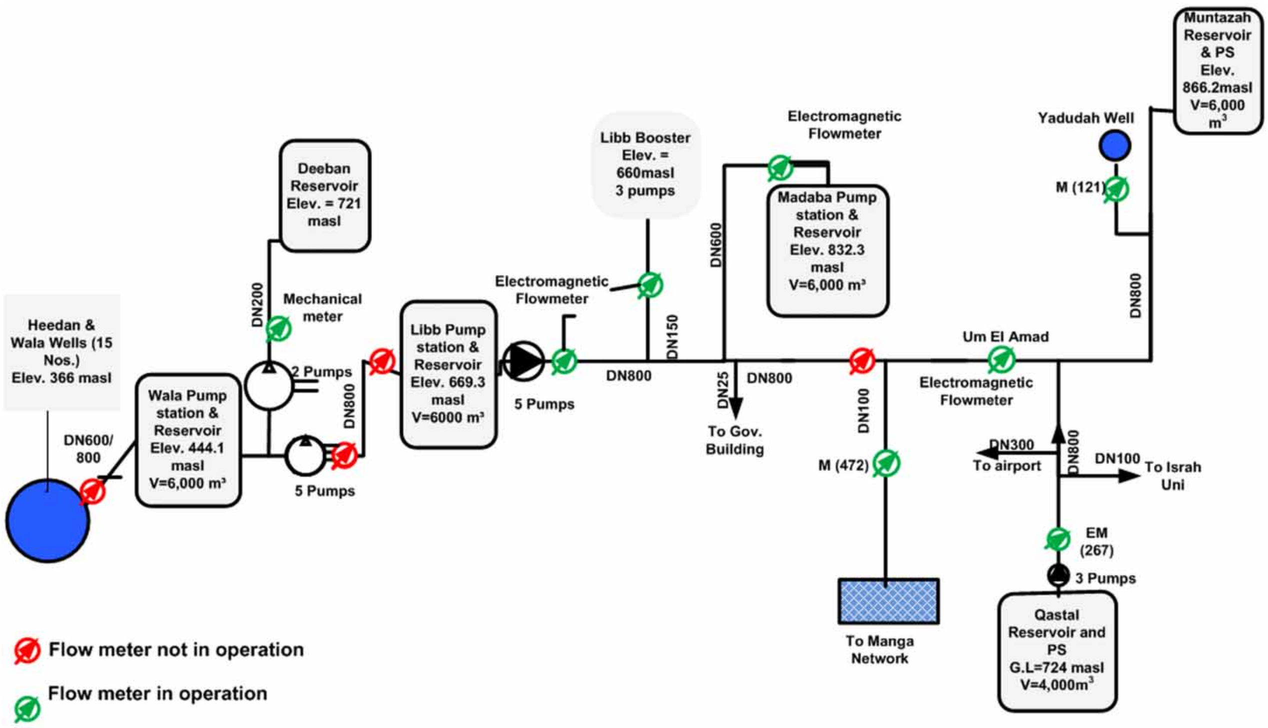

Figure 2 | Schematic of water supply system in Madaba, Jordan.

analysis of real losses (burst and background estimates) or minimum night flow measurements (Al-Washali *et al.* 2016).

Lambert (1994) proposed a concept for Real Losses Component Analysis, which is known as Breaks and Background Estimates (BABE), that helps water utilities quantify the real losses systematically based on the significant occurrence of leakage in the network where each leak is being affected by certain flowrates and time (Lambert 1994).

BABE was developed in order to estimate the real losses components based on logical assumptions, and is applicable for any water utility regardless of the conditions of the water network (Fanner *et al.* 2007).

However, the IWA water loss task force splits the real losses into three main categories with regards to the water system parts, whereas Lambert also divided the type of leakage into three main components:

1. reported leaks which are characterized by high flowrates and a short run time;
2. unreported leaks, which are characterized by a moderate flowrate, run time counts on the schema control of the water utility;
3. background leakage, which is characterized by a low flowrate, long run time, mostly found at water distribution fittings and joints.

All the components can be found in all parts of a water system, such as transmission pipes, house connections and reservoirs. Estimating the annual losses of each component depends on many parameters that affect the leakage rate, such as the operating pressure in the system as shown in Table 1 (Thornton *et al.* 2008).

The BABE concept has been improved internationally in recent years for water loss management. It has combined with another model in terms of pressure reduction which is called Fixed and Variable Area Discharge paths (FAVAD) (Lambert & Taylor 2010). The component analysis model can be used in different stages of the assessment, either in planning or operation and control phases. Therefore, this management tool will assist utility managers for leakage control programs on an economic basis and improve their performance management (Fanner *et al.* 2007).

The approach has shown that leaks can be divided into two main components; one 'direct' (bursts) that is given

Table 1 | Real losses estimation in a water system: main influencing components (Thornton *et al.* 2008)

Component of infrastructure	Background (undetectable) losses	Reported breaks	Unreported breaks
Mains	Length Pressure Min. loss rate/km[a]	Number/year Pressure Average flowrate[a] Average duration	Number/year Pressure Average flowrate[a] Average duration
Service reservoirs	Leakage through structure	Reported overflows: flowrates, duration	Unreported overflows: flowrates, duration
Service connections, main to edge of street	Number Pressure Min loss rate/conn.[a]	Number/year Pressure Average flowrate[a] Average duration	Number/year Pressure Average flowrate[a] Average duration
Service connections after edge of street	Length Pressure Min. loss rate/km[a]	Number/year Pressure Average flowrate[a] Average duration	Number/year Pressure Average flowrate[a] Average duration

[a]At standard pressure.

serious consideration due to its significant impact and the other is 'hidden' (background) leakage, which is too small and unavoidable to be observed (McKenzie & Lambert 2002; Farley 2008).

The Madaba water utility maintains a water distribution network database (i.e. assets, such as pipes, valves and materials) which corresponds to geographical locations. Due to the significant number of leaks in the Madaba network, a geographic information system (GIS) is utilized in order to record customers' complaints and leak events. A number of 5,642 leakage complaints were recorded in 2016 with an average repair time of 6 hours. There are many advantages of using a maintenance database to develop NRW strategies such as network optimization, leakage hotspot areas for investment and reducing water loss.

The total volume of leakage is calculated based on aggregating the number of leaks that have been recorded into the volume of leakage based on flowrates and running times, as shown in the equation below. The infrastructure condition factor (ICF) is considered in the model as a calibration factor based on the age of the network (Fanner & Thornton 2005):

$$\text{Volume of leakage} = \text{Number of leaks} * \text{Leak flowrate} * \text{Leak duration}$$

The Madaba water utility usually takes urgent action in response to leakage, especially in trunk mains where the pressure is high. The repair usually takes a short time, consequently, this leads to a minimized loss of water (Mathis *et al.* 2008). On the other hand, unreported breaks are characterized by a lower flowrate than reported breaks, but higher than background leakage. It cannot be reduced or detected until the water utility has put in place an intervention policy for active leakage control (ALC) (McKenzie & Lambert 2002).

The economic solutions are based on the IWA approach to manage and control real losses with four components: (1) speed and quality of repairs; (2) pressure management; (3) ALC; and (4) pipeline replacement. The model defines the economic level of leakage based on the Unavoidable Annual Real Losses (UARL) (background leakage) and the total leakage volume.

RESULTS AND DISCUSSION

The Component Analysis Model was designed by a Water Research Foundation (WRF) project to provide water utilities with a software tool to undertake a leakage component analysis and to identify the economic options for real loss reduction through improved speed and quality of leak repair, proactive leak detection and pressure management (WaterRF 4372: Real Loss Component Analysis: A Tool for Economic Water Loss Control).

This model has been used to evaluate options for implementing efficient and sustainable leakage control programs.

The model results should only be seen as a preliminary point for the proactive management of real losses. The preliminary real loss control strategy needs to be refined as more results become available.

The component analysis is structured to reflect the real losses components and the strategic options for NRW sustainable management of the Madaba water supply system in 2014. Based on the data provided to the model and the summary results of system components as shown in Table 2, the real losses calculated by water audit constituted 2.0 million m^3 and the water balance is presented in Table 3.

The results revealed that reported failures accounted for 37.2% while background leakage constituted 26.6%, which indicates the condition and shortcomings of the infrastructure, while the remainder was hidden and/or unreported leakage. The model has estimated the hidden losses in infrastructure which could not be detected or reported in the system based on the model assumptions.

According to the model, ICF ranges from 1 to 2.50 based on the age of distribution which is less than 50 years old. In the present study the ICF value is assumed to be 1 for Madaba. However, ICF has to be measured precisely by conducting field tests, taking into account different age factors, material and average pressure. ICF was calculated to reveal the amount of leakage by dividing the actual background leakage by unavoidable background leakage. Measuring unavoidable background leakage is difficult as it cannot be detected by the current tools utilized in assessments. Moreover, the recommended values of background rates are based on the 'good' condition of the distribution system. The average rate of rise of unreported leakage is a paramount parameter in order to carry out an intervention strategy. This variable can be misleading if it is not based on actual field measurements that evaluate the condition of the infrastructure. For Madaba's system, the rate of rise of unreported leakage is estimated to be 3.0 m^3/km of mains/day in a year based on water balances in successive years.

Although the utility has applied many techniques to detect and resolve leaks in the network, the component analysis revealed numerous reported failures in Madaba's distribution network, representing 37.2% of the total real losses, while background leakage and unreported failures constitute 26.6 and 36.20%, respectively. However, operating the network under high pressure in intermittent supply produces large losses in the network.

About 97% of failures were reported in service connections which account for 366 leaks/1,000 service connections/year, while the frequency of failures on the main lines constituted 48 leaks/100 km/year. The design of service connections, installation, and the quality of repairs and materials are low, which have contributed to the recorded frequency of failures.

Infrastructure failure frequency analysis

Based on the reported failure in the network, the results were below the failure frequency in system components and can be considered as a baseline for Miyahuna in order to relatively compare their operational management in the system in future. Moreover, the model provided an alarming indicator for the average failures in the system and the minimum failures that could occur in the distribution system against the optimized water supply network.

The frequency of water main bursts are significant, as shown in Table 4, and represent 48.3 leaks/100 km/year

Table 2 | Summary real losses component analysis

System component	Background leakage (ML)	Reported failures (ML)	Unreported failures (ML)	Total (ML)
Reservoirs	–	–	–	–
Mains and appurtenances	199.98	47.93	–	247.91
Service connections	336.04	700.77	–	1,036.82
Total annual real loss	536.02	748.71	–	1,284.73
Real losses as calculated by water audit				2,014.37
Hidden losses/unreported leakage currently running undetected				729.64

Table 3 | Madaba water balance according to IWA approach and BABE concept

		Billed Water Export 331.869 m^3				Revenue Water 331.869 m^3
				Billed Authorized Consumption 5,476.976 m^3	Billed Metered Consumption (water exported is removed) 5,443.003 m^3	Revenue Water 5,476.976 m^3
			Authorized Consumption 6,183.801 m^3		Billed Unmetered Consumption 33.973 m^3	
Madaba's Well Water 9,155.340 m^3				Unbilled Authorized Consumption 706.825	Unbilled Metered Consumption 11.733 m^3	
					Unbilled Unmetered Consumption 695.102 m^3	
					Unauthorized Consumption 32.936 m^3	
	System Input Water 9,399.762 m^3	Water Supply 9,067.893 m^3		Apparent Losses 869.722 m^3	Customer Metering Inaccuracies 823.179 m^3	
					Systematic Data Handling Errors 13.608 m^3	Non-Revenue Water (NRW) 3,550.110 m^3
			Water Losses 2,844.092 m^3		Background and Reported Leakage on Transmission and/or Distribution Mains 247.91 m^3	
Imported Water 244 m^3				Real Losses 2,014.370 m^3	Background and Reported Leakage on Service Connections 1,036.82 m^3	
					Total unreported/hidden Leakage on the network 729.64 m^3	

Table 4 | Failure frequency in mains

Total number of mains failures reported for water audit: Jordan Water Company – Miyahuna, Madaba, Jordan, 2014	415
Total length of mains (km)	859.0
Failure frequency Jordan Water Company – Miyahuna (number/100 km/yr)	48.3
Average failure frequency in North America based on literature review – WaterRF 4,372 (number/100 km/yr)	15.5
Failure frequency for optimized distribution systems (number/100 km/yr) (Friedman & Le Mieux 2010)	9.3

due to the aging infrastructure and high speed flows in the mains which increase the friction losses.

Repairing service connections

Service connections as shown in Table 5 represent the main challenge for Madaba water utility, and they constitute a considerable number of losses in the network. Reducing the failures in the network depends on replacing the deteriorated connections and repairing the system in a way that guarantees the reliability of the tertiary network.

Table 5 | Failure frequency in service connections

Total number of service connection failures reported for water audit: Jordan Water Company – Miyahuna, Madaba, Jordan, 2014	7,639
Total number of service connections (service connections)	20,869
Service connection failure frequency (number/1,000 service connections/yr)	366.0
AWWA Unavoidable Annual Real Losses (UARL) component of reported service line failures (number/ 1,000 service connections/yr)	3.75
Ratio of failure frequency to UARL break frequency	97.6

According to the water balance of Madaba, the total inflow of Madaba and Deeban directorates is sourced from Heedan and wall wells, distributing about 9.2 million m^3 while the total billed consumption amounts to 5.8 million m^3. The NRW for Madaba Governorate is 38.2% which constitutes about 3.5 million m^3. With a unit cost of 0.57 Jordanian Dinar (JOD), this amount corresponded to about 2.0 million JOD in losses in 2014. It is assumed that 70% of NRW are real losses and 30% accounts for apparent losses.

The Infrastructure Leakage Index ILI performance indicator considers, in addition to the network length, the number of customers and the average operating pressure in the network. This in fact helps in representing the actual system in the water utilities in Madaba.

The formula for calculation of the ILI is:

$$ILI = \frac{CARL}{UARL}$$

While Current Annual Physical Losses (CARL) can be measured and/or estimated, the UARL is calculated with the following formula:

$$UARL(l/d) = (18 \times Lm + 0.8 \times Nc + 25 \times Lp) \times P$$

where Lm = length of mains in km, Nc = number of service connections, Lp = total length of private pipe, property line to customer meter in km, P = average pressure in m, and DC = density of connections/km mains.

NRW constitutes 39.6% of the system input. The ILI for Madaba's system is 2.7 which describes the technical performance of leakage, but it does not consider the economic aspect. In order to achieve the minimum leakage that can save water and be cost effective, adequate investment and resources need to be taken into account.

ILI is influenced by many factors that affect its value, such as the connection density of the network, access to roads and the areas for locating and repairing and aging infrastructure (Farley 2003).

Other model's options: awareness, locations and repair time options

The model provided a pragmatic solution, as shown in Table 6, to reduce the running time of leaks in Madaba's distribution network by optimizing the repair time and considering the total time of awareness, locations, and

Table 6 | Optimizing the running leakage in Madaba network

Failures on mains	**Reported**
Total number of failures on mains in 2014	415
Average location and repair duration	1.0
Total volume lost (stemming from location and repair duration)	38.3
Total cost of volume lost (stemming from location and repair duration)	$18,209
What IF location and repair duration is reduced to	0.3
Percent reduction	70%
Potential related savings in leakage volume	26.8
Potential related savings in leakage volume cost	$12,746
Service line failures	**Reported**
Total number of failures on service connections in 2014	7,639
Average location and repair duration	1.5
Total volume lost (stemming from location and repair duration)	525.6
Total cost of volume lost (stemming from location and repair duration)	$249,572
What IF location and repair duration is reduced to	0.5
Percent reduction	67%
Potential related savings in leakage volume	350.4
Potential related savings in leakage volume cost	$166,381
Total potential savings if location and repair duration is reduced as simulated in the above sections (ML)	377.2
Total potential cost savings if location and repair duration is reduced as simulated in the above sections $/year	$179,127

repair times. The model revealed that the proactive leakage control in plugging chronic leakage can lead to an increase in revenue and lowering of water losses.

The leak run time plays a role in leakage reduction. For instance, around 179,127 $/year can be potentially saved as simulated by the study model when the leaking time is reduced from 1 day to 0.3 in mains, and from 1.5 days to 1 in service connection.

Reducing the location and repair time depends on customer support to report the leakage quickly and proactive leakage control to detect and repair the leaks in the network in an efficient time. Failures on the mains usually have a large impact on infrastructure due to high flowrates which require a quick response on the part of the utility to plug the leakage while failures on service connections produce low leakage rates which could be invisible or ignored by the public. Detecting the leakage and raising awareness of reporting leakage are paramount steps in saving the precious water.

Economic intervention

The model revealed an economic option, as shown in Table 7, for implementing proactive leakage control that is based on the budget capacity of Miyahuna Madaba. According to the model inputs, the user could only define two parameters of the cost of conducting the surveys and the estimated rate of unreported failures in the network. The model estimated the frequency of surveys per year and the required budget that should be invested for cost recovery.

The volume of real losses cannot be explained by recorded data since the amount of unreported leakage depends on active leak control and the actual UARL could be less than its empirical value. The ILI equals 2.69 for the entire system while CARL is more than twice the UARL. Therefore, it is recommended that leak detection be intensified to identify the unreported leaks.

The economic intervention of reducing the real losses in the network is recommended to optimize the surveillance system through district meter areas (DMA) for hydraulic monitoring instead of isolating the network and conducting a detailed investigation in order to define the root causes of a network's leakage (see Table 7). The model does not provide detailed expenses in calculating the customer retail unit cost and variable production cost. It is important to determine the actual retail unit cost of water without including the sewer costs in order to compare between different systems. It is recommended to develop the data validity scores by enhancing the metering system in the network in order to implement a reliable economic strategy for water loss reduction.

Pressure management

The model provided a robust option whereby pressure management has a direct impact on reducing the leakage rate without repairing a single leak in the network. The model

Table 7 | Economic intervention of reducing the real losses in the network

	Variable cost of real losses	Value	Unit cost
CV	Variable production cost (applied to real losses)	0.47	$/m^3
		474.85	$/ML
CI	Cost of comprehensive leak detection survey (excluding leak repair cost)	100.00	$/km
RR	Average rate of rise of unreported leakage	3.00	m^3/km of mains/day in a year
		2.58	ML/day in a year
	CI/CV	210.6	m^3/km
EIF	Economic intervention frequency [0.789 * (CI/CV)/RR] ^0.5	7.4	months
	Economic intervention frequency – average leak run time	113.2	days
	Economic percentage of system to be surveyed per year	161	%
ABI	Average annual budget for intervention (proactive leak detection)	138,508	$/year
EUL	Economic unreported real losses	291,688	m^3/year
	Economic Infrastructure Leakage Index (ILI)	2.1	
PRL	Potentially recoverable leakage (CARL-CRL-EUL-TBL-UL)	438.0	ML/year

Table 8 | Pressure management impact on real losses

	Existing pressure management policy	
Current average system pressure	60.0	meters (head)
Total annual real losses	2,014.4	ML/year
Value of real losses	956,524	$/year
Enter % of rigid pipes and service connections in system	52%	
ILI	2.7	
	Alternative pressure management policy	
Assumed reduction in average system pressure	10.0	meters (head)
Assumed % reduction in average system pressure	17%	
Real loss volume saved through alternative pressure management policy	335.7	ML/year
Value of real loss volume saved through alternative pressure management policy	159,421	$/year
Enter estimated cost of implementing alternative pressure management policy	1,000,000	$
Simple payback period for implementing alternative pressure management policy	6.3	Years

could give Miyahuna alternative scenarios, as shown in Table 8, for implementing cost-effective pressure modulation in the system. The costs are calculated based on previous NRW projects in Jordan.

Network pressure is a paramount parameter in the assessment of real losses. The pressure on the model is measured by calculating the average zone pressure (AZP) for the entire system that can be used as a preliminary step in order to reflect the impact on reducing the leakage (for measuring the leakage flowrates).

Pressure management could be an efficient approach to reduce the leakage in Madaba as it was reported that the network has been operating under high pressure. Therefore, the relation between pressure and leakage has to be measured under the existing conditions of the Madaba distribution network for each DMA to investigate both effects of shifting the DMAs from a pressure system to a gravity under intermittent water supply, as well as shifting from an intermittent system to a continuous supply. Therefore, comprehensive pressure measurements are required to achieve sustainable leakage management.

Study limitations

The present study has the following limitations:

1. The network pressure is a paramount parameter in the assessment of real losses. The pressure in the model is measured by calculating the AZP for the entire system that can be misleading for measuring the leakage flowrates.
2. Distance and reactive communication with customers has led to an increase in the awareness time of leakage and poor localization of complaints of leaks in GIS. Moreover, the lack of leak records of flowrates and pressure is not adequately documented.
3. The volume of real losses cannot be explained by recorded data since the amount of unreported leakage depends on active leak control and actual UARL which could be less than its empirical value. The ILI equals 2.69 for the entire system while CARL is more than twice the UARL. Therefore, it is recommended to intensify the leakage detection in the distribution network to detect all the unreported leaks.
4. ICF is calculated through dividing the actual background leakage by unavoidable background leakage. Measuring unavoidable background leakage is difficult since it cannot be detected by the current detection devices. Moreover, the recommended values of ICF are estimated based on the age and conditions of the distribution system.
5. The average rate in the rise of unreported leakage is a paramount parameter in order to carry out intervention strategy and it can be misleading if it is not based on actual field measurements.
6. The model does not provide detailed expenses in calculating the customer retail unit cost and variable production

cost. It is important to determine the actual retail unit cost of water without including the sewer costs in order to compare between different systems.

CONCLUSIONS

The design of water loss reduction programs should study the main drivers of NRW in intermittent water systems to provide utilities with a clear understanding of what can be done within the DMAs to achieve urban water security. Proactive leak detection has to be undertaken as a preliminary step every seven months according to the study model, taking into account the intervention frequency viability, but it can vary depending on the condition of the network and the natural rate of rise of the leakage. The schedule of the survey has to be updated and refined after determining the actual rate of rise of unreported failures in the distribution network. Quantifying the real losses in the network is key for intervention strategies by applying the Component Analysis of real losses into the Madaba water distribution system. Establishing proactive leak detection programs is necessary in order to identify hidden failures and unreported leakage in the water system. In the short term, it is paramount for the water utility to identify the data gaps by calibrating customer meters and bulk meters in order to reduce uncertainty and improve the billing system. Shifting into holistic NRW management is the main challenge for Jordan water utilities, which can be achieved through political will and support, backstopping from the upper management in addition to customer support and engagement in leak reporting.

Based on the model analysis and study findings, the following can be concluded:

1. Supplying water quantities in an intermittent system without proper asset management contributes to the high level of losses, deterioration of the network, and leads the utility into a feedback loop of decreased service delivery and little to no progress made in addressing NRW.
2. Effective leakage reduction needs effective data management with reliable information for the implementation of a long-term water loss reduction program.
3. Sub-standard work is a common issue, contributing to the high level of leakage and producing unnecessary leakage and decreasing the lifetime of assets. Sub-standard installation and repairs, especially in tertiary networks, is associated with different factors such as lack of qualified staff, lack of incentives, and absence of written standards, poor inspection and lack of repair materials.
4. The percentage of NRW in Madaba as a performance indicator (about 40% of system input) is misleading and inconsistent to assess the water losses in the intermittent water supply. It could be used as a financial indicator, but not as an operational indicator. Moreover, this indicator cannot be used to compare the performance among water utilities since each network has characteristics and conditions that influence the level of NRW. Furthermore, the indicator cannot differentiate between physical and commercial losses, or quantify the leakage and associated costs.
5. A break-even analysis has been used in water utilities as the most common accounting method in order to define the point at which operation and maintenance costs equal the revenue. Performing such standard methods turns out to be misleading in NRW management for two reasons:

    1. It may override the value of the opportunity cost in utilizing the water. The opportunity cost could be interpreted in three ways, the first is the opportunity cost of prohibiting sales to customers who would pay for drinking water. The second is the opportunity cost of environmental scarcity due to the high demand that leads to rising the operation cost for dispensable supply. The third is the opportunity cost of the price paid or high demand by the next generations due to population growth.
    2. It encourages the water utilities to identify NRW only as water for which they cannot receive any revenues straightaway because of the physical losses and commercial losses. This kind of approach may result in water being excluded from NRW calculations as authorized consumptions to save time and work. Consequently, the opportunity costs have to be internalized in water loss calculations.

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