ANALYSIS AND ASSESSMENT OF WATER LOSSES IN DOMESTIC WATER DISTRIBUTION NETWORKS

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ABSTRACT

Water scarcity is envisioned word over due to increasing urbanization, population overgrowth and climate change. Billions of cubic meters of treated water are lost worldwide from water distribution networks through leakage, which often lead to discontinuous water supply, either because of limited raw water availability or because of water rationing. The water companies all over the world and specially in a developing country like Egypt faces a lot of challenges from poor strategic management, limited financial resources and operational management, unskilled staff, low funding priority, insufficient customer service orientation, political interference and low independent regulations. This study is aiming to reduce the amount of physical leakage from the domestic distribution networks through the application of assessment methodology of the International Water Association (IWA) for water balance assessments and the databases of performance indicators, After the analysis of the data and application of the Infrastructure Leakage Index (ILI) method, the results, the ILI of the DMA were found to be high in which indicates that the network is Poor, Tolerable and immediate actions have to be done, and a management plan has to be set in order to reduce the water losses in the future.

Keywords: Non-Revenue Water, Water balance, District metered area, Minimum night flow, Infrastructure leakage index.

INTRODUCTION

Access to enough quantity of safe water is a vital human need, however according to the World Bank (Farley *et al.*, 2008) , each year more than 32 billion m^3 of treated water are lost through leakage from water distribution networks. An additional 16 billion m^3 per year are delivered to customers but not invoiced due to theft, poor metering, or corruption. In some low-income countries the water loss represents 50-60% of the total water supplied, with a global average estimated at 35%. Saving just half of this amount would supply water to an additional 100 million people without further investment. time of increasing demand, scarcity and climate change, from reaching their goals of full-service coverage, at a reliable level of service at an affordable price. Utilities in developed countries have managed to minimize their water losses to reach acceptable ranges unlike developing countries who are still facing a lot of problems (Makaya & Hensel, 2014), International Water Association (IWA) International Water Association (IWA) International Water Association (IWA). In order to reach the optimization of the water production costs, water utilities have to put a priority task to minimize the water losses in order to reduce the water treatment plant future extension needed to face the increase in demand.

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The potential benefits of suggesting alternatives for water distribution system management scenarios is to:

Managing the water distribution system (WDS) efficiently through various circumstances to prevent serious damages or long interruptions in service and It can result in significant financial savings for the water company (Farley e*t al*., 2008). The financial savings can be the result of following reasons:

1. Reduction of the associated costs of the water loss' production (i.e., chemical) and distribution (i.e., pumping).
2. Reduction of the operational costs of detecting and locating pipe burst.
3. Reduction of the associated costs of compensating affected local businesses due to pipe bursts.

In order to work on minimizing the amount of water losses, we have to fully understand the sources of losses and know where to start and how to compare it with other distribution networks (Petroulias *et al.*, 2016). Water Losses (WL) is divided into Real Leakage (RL), occurring in pipes, storage reservoirs, and customer connections or Apparent Losses (AL) occurring due to meters errors, errors in data handling, or un-authorized usage (Lambert, 2000), the sum of the volume of WL and the volume of Unbilled Authorized Consumption (UAC), which is the authorized usage that has no revenue, such as water used for fire- fighting or network cleaning, is called Non-Revenue Water (NRW).The components of water losses can be assessed by various methods. The International Water Association (IWA) and the American

Water Works Association (AWWA) have suggested water audit tools and methodologies to assess the performance level of a WDS. These methodologies include Water Balance (WB) assessments and databases of Performance Indicators (PIs).

This paper discusses the application of different methods of analysis and assessment of physical leakage from water distribution networks as the first step of a leakage reduction strategy then verify on a chosen water distribution network as a DMA using the method of Minimum night flow along with The Infrastructure Leakage Index (ILI) developed by the IWA Water Losses Task Force as a performance indicator to detect and manage physical leakage.

MATERIAL AND METHODS

1. Water balance

Any discussion relating to water losses must start with a clear definition of the water balance components (Winarni, 2009) (Farley, 2001) . The main definitions are: System Input Volume, Authorized Consumption and Water Losses which is the difference between “system input volume” and “authorized consumption”, although water losses consist of real and apparent losses.

- Real losses: are the physical losses of leaks, bursts and overflows up to the point of customer metering.
- Apparent losses: consist in all types of inaccuracies (input, output, customer meters), and unauthorized consumption (illegal use).

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- Non-revenue water is the annual volume of total losses and unbilled authorized consumption.

The International Water Association (IWA) has developed a standard international water balance structure and terminology that has been adopted by national associations in many countries across the world (Lambert & McKenzie, 2002)(Table 1).

Table 1: The IWA Water Balance

<table>
<tr><td rowspan="9">SYSTEM INPUT VOLUME</td><td rowspan="4">AUTHORIZED CONSUMPTION</td><td rowspan="2">BILLED AUTHORIZED CONSUMPTION</td><td>BILLED METERED CONSUMPTION</td><td rowspan="2">REVENUE WATER</td></tr>
<tr><td>Billed unmetered consumption</td></tr>
<tr><td rowspan="2">Un-billed authorized consumption</td><td>Unbilled metered consumption</td><td rowspan="7">Non-revenue water</td></tr>
<tr><td>Unbilled unmetered consumption</td></tr>
<tr><td rowspan="5">Water losses</td><td rowspan="2">Apparent losses</td><td>Unauthorized consumption</td></tr>
<tr><td>Metering inaccuracies</td></tr>
<tr><td rowspan="3">Real losses</td><td>Leakage on transmissions and/or distribution mains</td></tr>
<tr><td>Utility storage tanks leakage</td></tr>
<tr><td>Service connections leakage up to customer metering</td></tr>
</table>

Lambert & Taylor, 2010

2. IWA Performance Indicators for NRW and its Components

The 1st Edition of 'Performance Indicators for Water Supply Systems' (Kölbl, 2007), proposed 133 Performance Indicators covering a wide range of Water Utility functions. Table (2) shows the small subset of NRW and Water Loss Performance Indicators, developed by the 1st IWA Water Loss Task Force (Lambert, 2000) which were included in the 1st Edition of the PIs Report.

Table 2 : Recommended performance Indicators, for different purposes

INDICATOR	**PI GROUP**	**RECOMMENDED UNITS**	**COMMENTS**
Non- revenue water by volume	Financial (Fi)	Volume of non-revenue water as % of the system input volume	Can be calculated from simple water balance
Non-revenue water by cost	Financial (Fi)	Volume of non-revenue water as % of annual cost of the running system	Allows separate values/m^3 for components of non-revenue water
Water losses	Operational (Op)	m^3/service connection/year	Same units as authorized consumption
Apparent losses	Operational (Op)	m^3/service connection/year	Same units as authorized consumption
Real losses	Operational (Op)	Liters/service connection/day	Allows for intermittent supply situations, use 'per km' if the connections are less than 20 connection/ km
Infrastructure leakage Index (ILI)	Operational (Op)	Ration of real losses to technical achievable annual low-level real losses	Technical achievable low-level annual real losses equal the best estimate of UARL includes system- specific allowance for connection density, customer meter location on service, and current average pressure
Inefficiency of use of water resources	Water resources (WR)	Real losses as % of system input volume	Unsuitable for assessing efficiency of management of distribution system

PI= Performance Indicators
(IWA, 2000)

3. Minimum Night Flow (MNF) analysis

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After the construction of a district metered area DMA (in case of more than one supply water source a division strategy should be implemented), several flowmeters and pressure data loggers are installed at certain points of the network (Mirats-Tur et al., 2014), The minimum night flow MNF is the lowest flowrate of water through the DMA over the day, which occurs at night usually between 2.00 and 4.00 am, when most of the customers are inactive (AL-Washali et al., 2020). The flow at this time is mainly leakage, to obtain the rate of the real losses during the day, the leakage rate is adjusted using a pressure correction factor called night–day factor (NDF), which can be calculated using Eq. (2.1) (United Nations Development Programme., 2003). The pressures in the NDF should include the pressure during the whole day and represent the normal actual situation in the DMA.

$$F = \sum_{i=1}^{i=23} (P_i/P_{min})^{N1} \tag{2.1}$$

Where NDF is the night day factor, P_i is the average pressure during the day hours, and P_{min} is the average pressure during the minimum night hours, and N1 is leakage exponential that assumed to be 1 in this study.

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4. Methods used to assess water losses:

Several performance indicators were used to assess water loss from pipe network(Brown, 2007). The first method is the percentage of water loss compared to the total annual supply volume of water.

$$\mathbf{UFW = CARL/SIV*100\ \%} \qquad \mathbf{(2.2)}$$

Where, UFW is the percentage of un-accounted for water (%), CARL is the current annual real losses volume (m3/year), and the SIV is the supply input volume (m3/year).

The second method is individual real loss indicator (Klosok-Bazan *et al.*, 2021), which can be expressed with the following formula:

$$\mathbf{RLB = CARL/\ (L_{m} + L_{r})\ *365\ (m^{3/}km/d)} \qquad \mathbf{(2.3)}$$

Where, RLB is the real losses balance indicator (m3/km/d), CARL is the current annual real losses (m3/year), Lm is the total length of distribution main pipes (Km), and Lr is the length of connection pipelines (Km).

The third one is Infrastructure Leakage Index (ILI), it provides clearer image about the analyzed system, as it takes into consideration the mains length, the customer meter location (relative to the property line), and the average operating pressure of the network.

ILI is also meaningful in terms of basis for performance comparison, benchmarking, target settings and analysis.

$$\mathbf{ILI=CARL/UARL} \qquad \mathbf{(2.4)}$$

Where, CARL is the Current Annual Real Losses (m3/year) and UARL is the Unavoidable Annual Real Losses (m3/year). The IWA workgroup suggested that this performance indicator ILI ranges from 1 to 5, where 1 indicates that the system is at very low level of water losses, while above 5 indicates that the system is at high risk in terms of water losses.

Unavoidable Annual Real Losses (UARL)(Kabaasha et al., 2016), which reflect the amount of water losses in which it is uneconomically unjustified trying to reduce, it is the summation of three components;

1. Unavoidable leakage from main pipelines and lines without connections (18 l/km/d/m pressure).
2. Unavoidable leakage from connection to the edge of the street (0.8 l/connection/day/m pressure).
3. Unavoidable leakage from the edge of the street to the customer meter (25 l/km/d/m pressure).

This indicator is expressed as follows:

$$\mathbf{UARL = (18*(L_m + L_r) + 0.8* N_p + 25* L_p) * P * 0.365} \qquad \mathbf{(2.5)}$$

Where, UARL is the calculated Unavoidable Annual Real losses (m^3/year), L_m is the length of the main pipelines (km), L_r is the length of connection pipeline (km), N_p is the number of private connections, L_p is the total length of the private pipelines, and P is the average operating pressure of the system.

Table 3: Real losses assessment matrix

ILI		**BAND**	**GENERAL DESCRIPTION OF CATEGORIES**
Developed countries	**Developing countries**		
1-2	1-4	A	Further losses reduction may be uneconomic unless there are shortage, careful analysis is needed to identify cost-effective improvement.
2-4	4-8	B	Potential for marked improvement, consider pressure management, better active leakage control practices, and better network maintenance.
4-8	8-16	C	Poor leakage record, tolerable only if water is plentiful and cheap, even then, analyze level and nature of leakage and intensify leakage reduction.
>8	>16	D	Very inefficient use of resources, leakage reduction programs are imperative with high priority.

ILI= Infrastructure leakage Index

World Bank Institute, 2009

The approach of UARL and ILI is now widely used because of its allowance of using 3- keys system specific parameters which are: length of mains - number of connections – location of customer meters along with the average pressure of the system. Separating the effect of pressure from the infrastructure conditions of the network has introduced clear vision to the technical analysis without much effort. The approach is being used for international, national, and within the system comparisons (Lambert & McKenzie, 2002) .

1.1 Description of the Case study area

The chosen study area is Met Afif which a small village located at Monufia governorate in Egypt at 30°23'16.0584"E 31°5'43.8864"N fig. (1&2), whose population is (8222 capita) and its area is (47.3 hectares). The network consists of old pipes of diameters from 100 to 200 mm, total length of 21 km, and about 1500 house connections. Met Afif is a residential area having a school and few administrations and commercial buildings. It has a metering system of 2497 working meters out of 3415 meters in total (73.11%). The elevations of the junctions in the network varies between 10 and 17 meters above the sea level.

Met Afif village was chosen as it has single inlet for water supply and no outlet, also it meets with the District Metered Area (DMA) criteria as follows:

- It is isolated, it has one inlet point and there was a flow meter to measure the flow rate.
- Size of the area: the size was limited to enable proper monitoring of the network.

1. The chosen area had a high visible water leakage points and operating water pressure were not less than 1.5-2 bars.
2. Appropriate network base map was available indicating the network data.
3. The selected area had a highly water meter efficient system.
4. The number of house connection was near the required range 1000-1500 connections.

Figure (1): Monufia Governorate

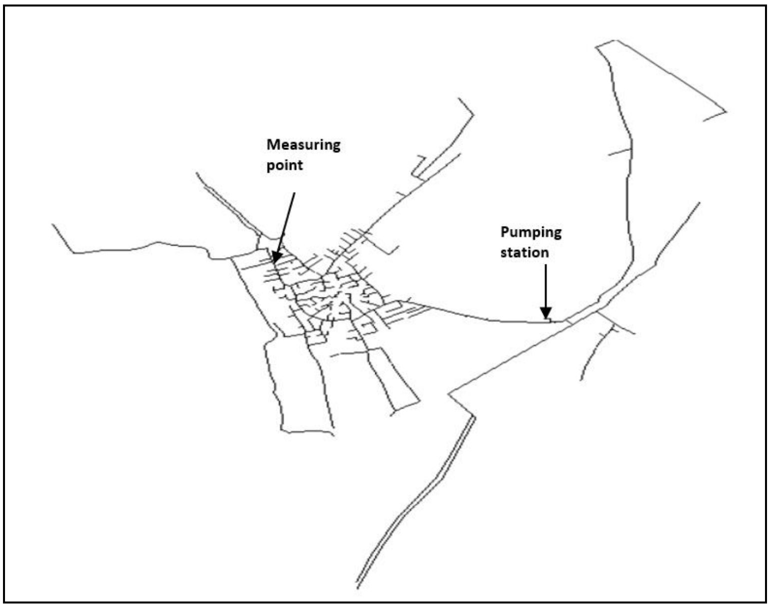

Figure (2) Met Afifi Water Distribution Network

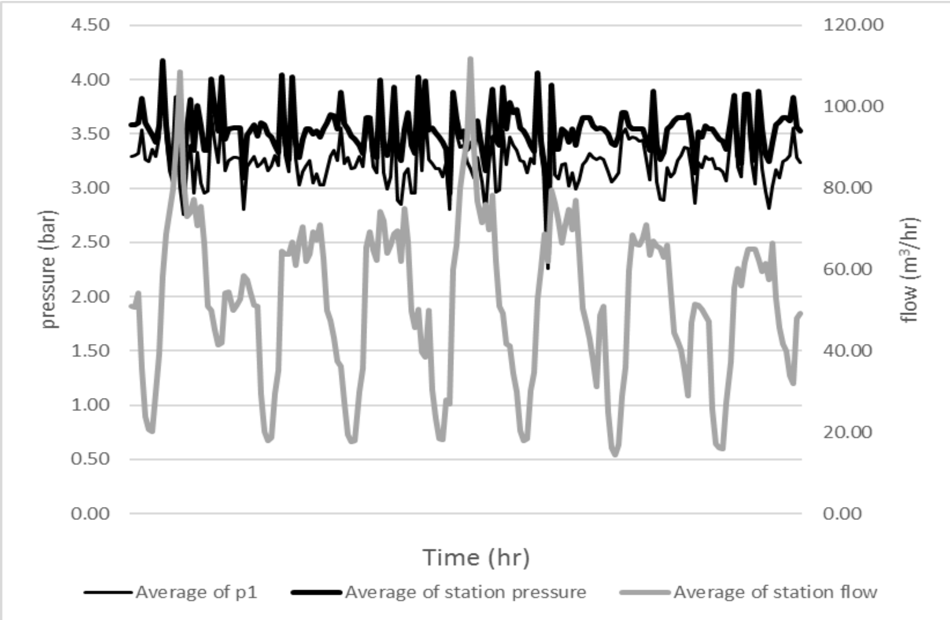

Figure (3): The recorded data of flow and pressure of one month (October 2019)

Measurements were carried out on the inlet pipe to the network during a period of 3 months, along with the water pressure every 5 minutes using data loggers and mechanical flowmeter. After analysis of the available data for the three months, and excluding the fault data and the days that had errors or special circumstances of network maintenance or problems in the pressure loggers; the data for October was chosen to represent the network, and any change in the seasonal factor of consumption shall be investigate in further studies.

Recording data of the billed metered and unmetered consumption of the customers were collected and analyzed along with the status of the property meters at each customer property. Table (4) shows a sample of the recorded data of the billing department in Monufia Water Company, each record is documented with the customer's name, the type of meter whether it is domestic or commercial, and the number of properties served by each meter.

Table 4: Example of billing system

NAME OF CUSTOMER	TYPE OF CONSUMPTION	NUMBER OF PROPERTIES	PREVIOUS METER READING	EXISTING METER READING	CONSUMPTION VOLUME(M^3)
Refaat Mohamed Ali	Domestic	1	3240	3260	20
Khaled Mohamed Ali	Domestic	3	1620	1650	30
Youssouf Elsayed Basiony	Domestic	2	4530	4550	20
Dawood Mohamed Dawood	Domestic	2	4055	4075	20

RESULTS AND DISCUSSION

1. Water Balance Analysis

A full water balance analysis was made using the recommended table by IWA. And the data from billing department at Monofya governorate and by analyzing the data of the chosen period (October 2019), along with the field data of input flow rate. All the input data were fed into Microsoft Excel, and the following results were obtained.

Table 5: water balance analysis

SUPPLY INPUT VOLUME	AUTHORIZED CONSUMPTION	BILLED AUTHORIZED CONSUMPTION	BILLED METERED CONSUMPTION	REVENUE WATER
		29206	Billed Unmetered Consumption	29206 m3/month
	29206	Unbilled Authorized Consumption 0	Unbilled Metered Consumption	Non-Revenue Water
	m3/month	m3/month	Unbilled Unmetered Consumption	
38429	Water Losses	Apparent Losses	Unauthorized Consumption	
m3/month		1280 m3/month	Customer Meters Inaccuracies	
	9223	Real Losses	Leakage on Main Pipes	9223
	m3/month	7944	Leakage at Reservoirs	m3/month
		m3/month	Leakage on Service Connections	

The following results were obtained:

- The total input flow rate was 38429 m^3/month.
- The total revenue water was 29206 m^3/month.

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- Percentage of NRW was found to be 24% (9223 m^3/month).
- Physical losses 20.67% (7943.326m^3/month).
- Commercial losses 3.33% (1279.674m^3/month).

2. Using The Night Flow Data to assess Real Losses

First it was arranged to measure night flows into the DMA, second a hydraulic model was made using WaterGEMS program to estimate an average pressure (AZNP) at night in the Zone at the 'Average Zone Point (AZP).

Measuring the Minimum Night Flow MNF over 3 hours between 01and 03 am, together with the Average Zone Night Pressure (preferably over several nights, and use the average values), then estimate of Customer Night Consumption in liters/connection/hour (assumed as 2.0 liters/conn/hour in this study)

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Table 6: Calculation of Snapshot Night Leakage Rate

CALCULATION OF THE SNAPSHOT NIGHT LEAKAGE RATE				
number of service connection=	1500	liters/sec	m^3/hour	liters/con. /Hour
length of mains (km)=	21			
when AZNP (m)=	35			
minimum night flow MNF		4.38	15.77	10.52
assessed minimum night consumption CNCa		0.83	3	2
snapshot night leakage rate = MNF-CNCa		3.55	12.77	8.52

AZNP (m)=Average Zone Night Pressure

3. Obtaining of daily leakage flow rate

Table 7*:* Multiplying the Night Leakage Rate (NLR) by Night Day Factor (NDF) to obtain snapshot daily leakage

MULTIPLY NIGHT LEAKAGE RATE (NLR) BY NIGHT DAY FACTOR (NDF) TO OBTAIN SNAPSHOT DAILY LEAKAGE	**M^3/HOUR**	**HOURS/DAY**	**M^3/DAY**
Night Leakage Rate (NLR)	12.768		
Night - Day Factor (NDF)		19	
snap shot daily leakage = NLR * NDF			242.592

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4. **Assessment of Real Losses using ILI and World Bank Institute Bands**

The ILI is the ratio of the Current Annual Real Losses (CARL) divided by the Unavoidable Annual Real Losses (UARL), using equations (2.4) & (2.5) it can be calculated as:

UARL = (18*21+0.8*1500) *35/24/1000 = 2.3 m^3/hour

ILI = Snapshot Night Leakage Rate NLR / UARL

So, ILI = 12.77/2.3 = 5.55 According to the physical water losses matrix developed by the world bank institute; the study area is located at **Group C** (refer to table 3).

CONCLUSION

In summary, the increase of demand on potable water supply puts a great pressure on the limited water resources available and the water supply systems. Most of this water supply systems are aging specially in the developing countries, consequently, a huge amount of water is lost due to leakage. Therefor this paper aimed at focusing on the analysis and assessment of this leakage in order to start the management strategy in order to control and reduce the amount of water lost through physical leakage.

The continuous monitoring of the hydraulic characteristics of the water network gives a more reliable data base to fully understand and control the water supply system.

There are many methods to analyze the water leakage, choosing of the method depends on the availability of data and the level of accuracy aiming for in the light of the human and financial resources available.

As for the study area, the amount of water that is non-revenue was found to be 24% of the total input supply volume, which for a developing country represent a huge burden on the water company trying to compensate that financial gap.

The leakage infrastructure index showed its performance in evaluating the water network and its need for leak reduction strategy, in this case study the ILI was found to be 5.5, which classify the DMA as grope C in the IWA categorizing matrix (table 3), therefore further work has to be done in order to control and reduce this level.

The further studies will include implementing a leakage reduction method on the case study in aim of reaching the most economical method to be carried out, considering both financial and human resources available at the water company in order to put the guide lines for generalizing those steps on other water supply systems.

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تحليل وتقييم فواقد المياه بشبكات توزيع مياه الشرب

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المستخلص

تعاني بعض الدول عالميا من ندرة المياه بسبب زيادة التحضر وزيادة النمو السكاني وتغير المناخ. تُفقد مليارات الأمتار المكعبة من المياه المعالجة في جميع أنحاء العالم من شبكات توزيع المياه من خلال التسرب، مما يؤدي غالبًا إلى انقطاع إمدادات المياه، إما بسبب محدودية توافر المياه الخام أو بسبب تقنين المياه. تواجه شركات المياه في جميع أنحاء العالم وخاصة في دولة نامية مثل مصر الكثير من التحديات مثل: سوء الإدارة الاستراتيجية، الموارد المالية المحدودة، الإدارة التشغيلية والموظفين غير المهرة، أولوية التمويل المنخفضة، التوجيه غير الكافي لخدمة العملاء، التدخل السياسي واللوائح المستقلة المنخفضة. تهدف هذه الدراسة إلى تقليل كمية التسرب الفيزيائي من شبكات التوزيع المحلية من خلال تطبيق منهجية التقييم الخاصة بالاتحاد الدولي للمياه (IWA) لتقييم توازن المياه وقواعد بيانات مؤشرات الأداء، بعد تحليل البيانات وتطبيقها. تم العثور على طريقة مؤشر تسرب البنية التحتية (ILI) ، والنتائج ، و ILI لـ DMA عالية مما يشير إلى أن الشبكة ضعيفة، وأنه يجب القيام بإجراءات فورية ، ويجب وضع خطة إدارة لتقليل فاقد المياه في المستقبل.

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