Alexandria Engineering Journal (2017) 56, 601–612

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Alexandria Engineering Journal

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ORIGINAL ARTICLE

Pressure control for minimizing leakage in water distribution systems

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Received 6 May 2017; revised 7 June 2017; accepted 15 July 2017
Available online 1 August 2017

KEYWORDS

District measure area;
Infrastructure leakage index;
Leakage;
Pressure management;
Water supply networks

Abstract In the last decades water resources availability has been a major issue on the international agenda. In a situation of worsening scarcity of water resources and the rapidly increasing of water demands, the state of water losses management is part of man's survival on earth. Leakage in water supply networks makes up a significant amount, sometimes more than 70% of the total water losses. The best practices suggest that pressure management is one of the most effective way to reduce the amount of leakage in a water distribution system. The approach presented in this study is aimed at modeling leakage as a function of pressure and pipe length, calibrating leakage coefficient, using fixed pressure reducing valves (PRVs) to develop pressure fluctuation and developing WaterCAD scenarios to minimize leakage through the most effective settings of PRVs. This approach was applied on a district metered area (DMA) in Alexandria, Egypt. The application of this approach produced some encouraging results, where the leakage through DMA was dropped by 37% for the best scenario. Thus, this approach is recommended as a decision support tool for determining a desirable solution for leakage reduction.

1. Introduction

Globally, water losses from water distribution systems are reaching alarming levels. They are made up of various components including physical losses (leakage), unauthorized consumption and apparent losses [1]. Leakage makes up a large part, sometimes more than 70% of the total water losses [1].

Leakages are the annual volumes lost through all types of leaks, bursts and overflows up to the point of customer metering [2]. They are caused by lack of active leakage control (ALC), excess pressure, poor operations and maintenance, poor quality of underground assets, vibration and traffic loading and Corrosion [3].

Bursts and background estimates (BABE) philosophy provides a pragmatic and simple approach to the very complex problem of leakage from water distribution system [4].

BABE concept recognizes that the annual volume of physical losses consists of numerous leakage events. Each

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

http://dx.doi.org/10.1016/j.aej.2017.07.008
1110-0168

individual loss volume is influenced by flow rate and duration of leak run time before it is repaired [5].

In BABE analyses, components of leakage can be categorized into three categories [5–7]:

- Reported breaks and leaks: They typically have high flow rates and short run time before they are reported to the utility either by the general public or the water utility's own staff. They are visibly evident and disruptive.
- Unreported breaks and leaks: They have moderate flow rates and a long run time. They are located by leak detection team as part of their active leakage control (ALC) program.
- Background losses: They are individual events (from joints, fittings, and small cracks) with flow rates too low to be detected by traditional acoustic leak detection techniques. They will continue to flow either detected by chance or until they gradually worsen to a point where they can be detected.

The total leakage from small hidden leaks and undetected breaks is significantly greater than from reported breaks. Main breaks that surfacing and causing supply disruptions are reported quickly and repaired within a short time. Conversely, small hidden leaks and undetected breaks may run for much longer periods until they are detected [7].

The BABE concepts are most effective when applied in conjunction with the following [4]:

- Fixed area variable area discharges principles.
- The infrastructure leakage index.
- Unavoidable annual real losses principles.

Infrastructure leakage index (ILI) can be defined as the current annual real losses (CARL) divided by the unavoidable annual real losses (UARL) [8]. The volume of unavoidable annual real losses (UARL) represents the lowest technically achievable annual real losses for a well-maintained and well-managed water distribution system [9].

There are four fundamental leakage management practices that will constrain physical losses including pressure management, speed and quality of repair, active leakage control (ALC), and asset management [2].

Pressure management is one of the most influential and cost-effective activities of reducing leakage. It can be defined as the practice of managing water distribution system pressures to the optimum levels of service ensuring sufficient and efficient supply to consumers [10].

The general objectives of pressure management for leakage minimization are three-fold [5,6]:

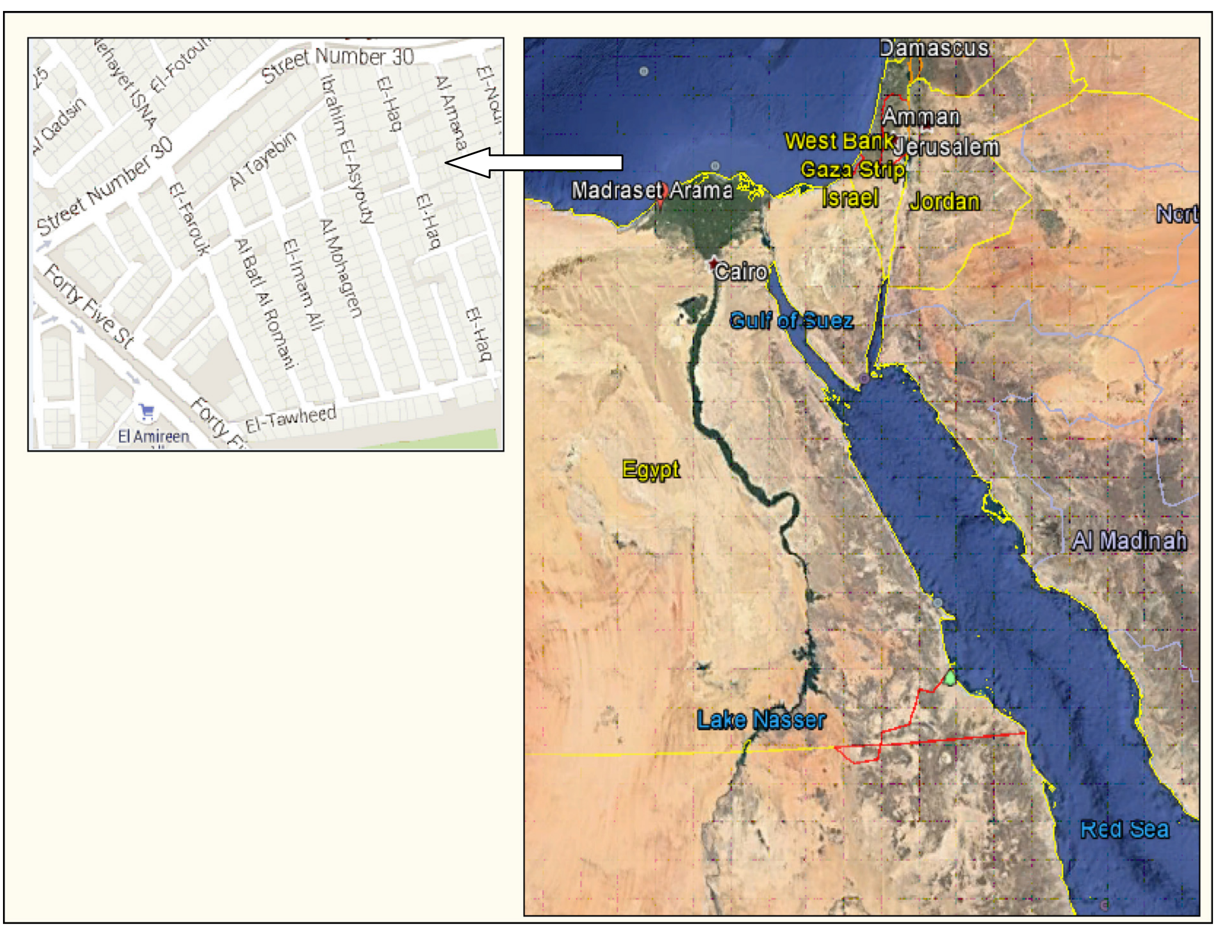

Fig. 1a Arama (DMA), Alexandria, Egypt.

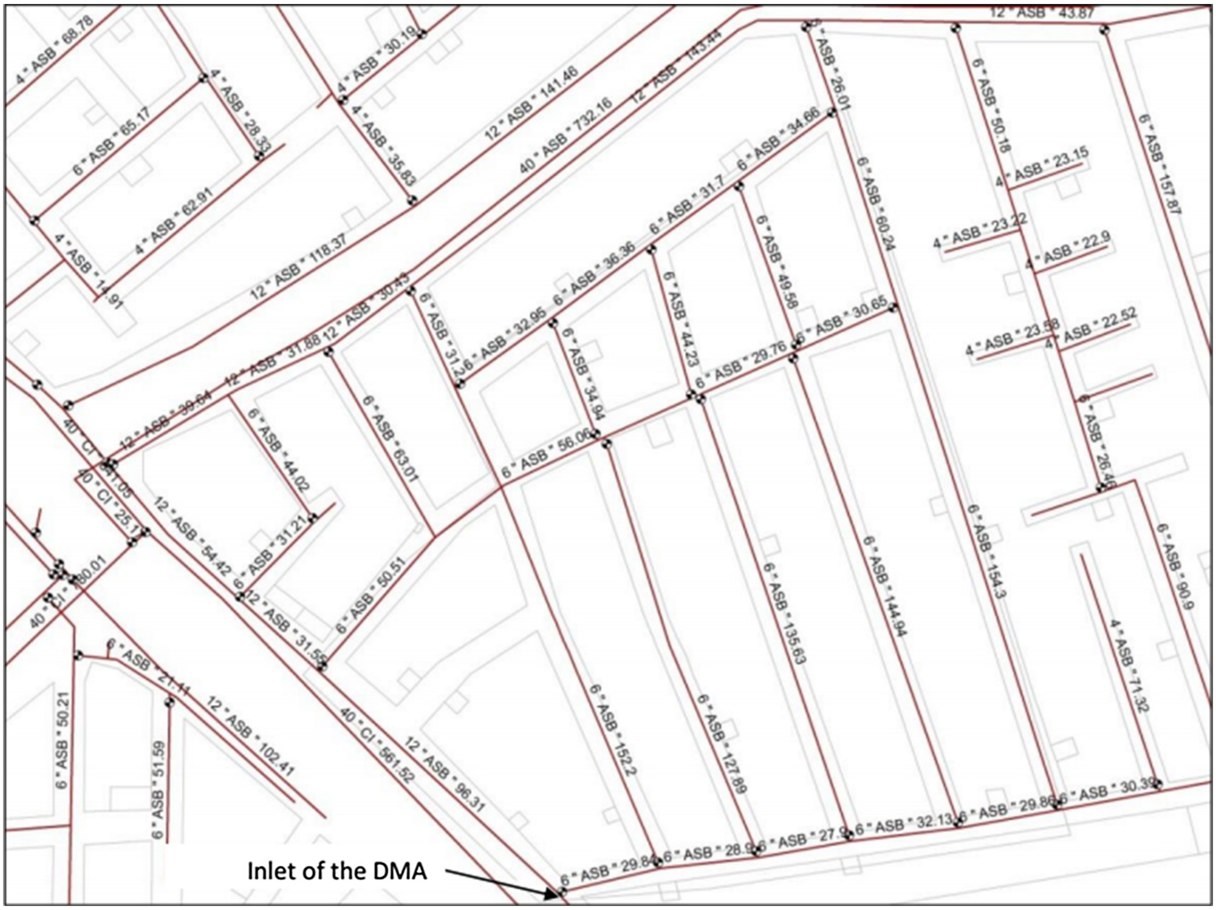

Fig. 1b Arama (DMA) existing piping system.

Table 1 Real loss assessment matrix [16].

Technical performance category		ILI	Litres/connection/day (when the system is pressurized) at an average pressure of				
			10 m	20 m	30 m	40 m	50 m
Developed	A	1–2		< 50	< 75	< 100	< 125
Country	B	2–4		50–100	75–150	100–200	125–250
Situation	C	4–8		100–200	150–300	200–400	250–500
	D	> 8		> 200	> 300	> 400	> 500
Developing	A	1–4	< 50	< 100	< 150	< 200	< 250
Country	B	4–8	50–100	100–200	150–300	200–400	250–500
Situation	C	8–16	100–200	200–400	300–600	400–800	500–1000
	D	> 16	> 200	> 400	> 600	> 800	> 1000

- Reduce background leakage which is acoustically undetectable seeps at pipe joints and small cracks. It cannot be economically repaired on an individual basis.
- Reduce the rate of new leaks and breaks which occur on mains and service connections, due to diminished stress on the pipes.
- Reduce the flow rate from any leaks and breaks.

The most common methods of pressure management include establishing zone boundaries, fixed outlet pressure control valves, pump and level control, time modulated control valves and flow modulated control valves [11]. However, one of the most common and effective method is using Pressure Reducing Valves (PRVs) [2].

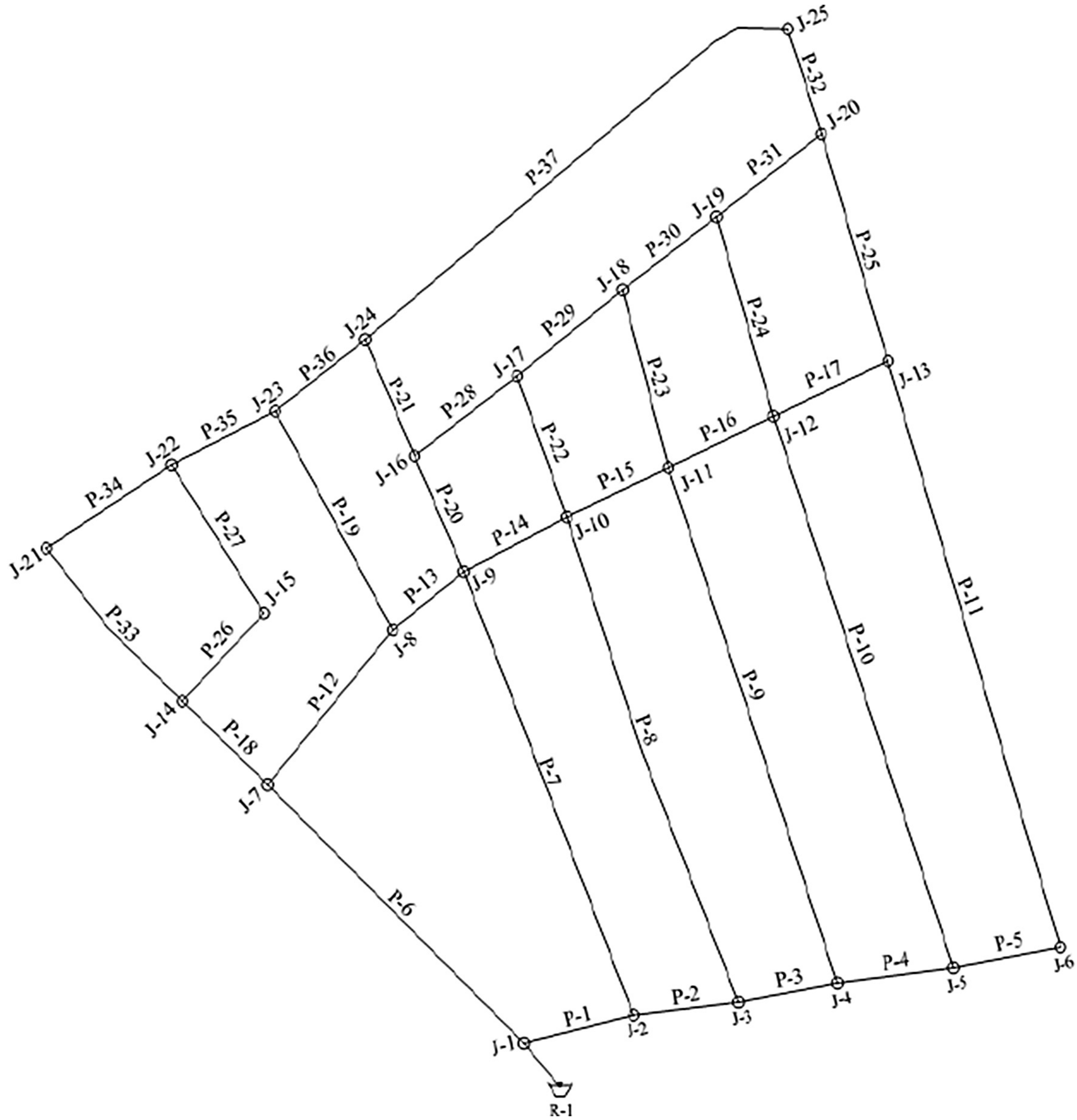

Fig. 2 WaterCAD set up model.

The practice of controlling pressure to minimize leakage in water distribution systems is not new, short tests of pressure: leakage relationships on 20 small sectors of all-metal Japanese distribution systems, analyzed and presented in the form of a simple Power Law (Leakage L varies with Pressure P^{N1}) [10]. The value of the exponent N_1 can be typically varies between 0.5 and 2.79 with a median of 1.15 depending on the mixture of leaks and the dominant type of leaks (fixed area leaks: $N_1 = 0.5$; longitudinal split which opens in one dimension: $N_1 = 1.5$; linear-radial opening: $N_1 = 2.0–2.5$) [10].

A variety of different concepts have been proposed to explain the diversity of pressure: leakage rate relationships including the widely used fixed and variable area discharge (FAVAD) model [12]. This model offers a means to demonstrate the sensitivity to pressure of different leaks, and to quantify the change of area of elastically deforming leaks subject to hydraulic pressure loading [12].

The BABE and FAVAD principles are important management tools, assisting water utilities to improve their leakage management strategies that are appropriate for their water distribution system characteristics [5].

The increase or decrease of leakage due to a change in pressure can be computed by FAVAD concept as the principle of conservation of energy. This principle dictates that the velocity of a jet of water passing through an orifice varies with the square root of the pressure [13].

There is a Global trend towards study the leakage in water distribution systems and raise the water utilities awareness level on the importance of minimize the quantity of leakage. In Egypt, water utilities start to establish their strategy to

Table 2 Characteristics of pipes within the water CAD model.

Label	Start junction	End junction	Length (m)	Diameter (m)
P-1	J-1	J-2	30	0.154
P-2	J-2	J-3	29	0.154
P-3	J-3	J-4	28	0.154
P-4	J-4	J-5	32	0.154
P-5	J-5	J-6	30	0.154
P-6	J-1	J-7	96	0.3048
P-7	J-2	J-9	152	0.154
P-8	J-3	J-10	128	0.154
P-9	J-4	J-11	136	0.154
P-10	J-5	J-12	145	0.154
P-11	J-6	J-13	154	0.154
P-12	J-7	J-8	51	0.154
P-13	J-8	J-9	25	0.154
P-14	J-9	J-10	56	0.154
P-15	J-10	J-11	33	0.154
P-16	J-11	J-12	30	0.154
P-17	J-12	J-13	31	0.154
P-18	J-7	J-14	32	0.3048
P-19	J-8	J-23	63	0.154
P-20	J-9	J-16	32	0.154
P-21	J-16	J-24	31	0.154
P-22	J-10	J-17	35	0.154
P-23	J-11	J-18	44	0.154
P-24	J-12	J-19	50	0.154
P-25	J-13	J-20	60	0.154
P-26	J-14	J-15	31	0.154
P-27	J-15	J-22	44	0.154
P-28	J-16	J-17	33	0.154
P-29	J-17	J-18	36	0.154
P-30	J-18	J-19	32	0.154
P-31	J-19	J-20	35	0.154
P-32	J-20	J-25	26	0.154
P-33	J-14	J-21	54	0.3048
P-34	J-21	J-22	40	0.3048
P-35	J-22	J-23	32	0.3048
P-36	J-23	J-24	30	0.3048
P-37	J-24	J-25	143	0.3048

Table 3 Demand and elevation of junctions within the water CAD model.

Label	Demand (L/sec)	Elevation (m)
J-1	0.29	0
J-2	0.53	0
J-3	0.47	0
J-4	0.59	0
J-5	0.70	0
J-6	0.31	0
J-7	0.45	0
J-8	0.83	0
J-9	0.64	0
J-10	0.88	0
J-11	0.90	0
J-12	0.95	0
J-13	0.48	0
J-14	0.21	0
J-15	0.35	0
J-16	0.28	0
J-17	0.34	0
J-18	0.36	0
J-19	0.37	0
J-20	0.22	0
J-21	0.15	0
J-22	0.23	0
J-23	0.27	0
J-24	0.16	0
J-25	0.70	0

reduce physical losses in water distribution system. They face a lot of barriers including the high cost of losses management, shortage of skilled labor for such technologies, difficulties of dealing with looped complicated network, old of infrastructure components and lack of maps and data. Thus water utilities

Fig. 3a Base scenario.

decided to divide the network into small sectors called District Measure Area (DMA) to facilitate dealing with the physical losses problem [14].

The aim of this study is to model leakage depending on understanding the hydraulics of leaks and how to incorporate that hydraulics into existing models which attempt to model leakage as a function in pressure and pipe length.

A District Metered Area (DMA) in Alexandria, Egypt was analyzed using WaterCAD, Version 8 hydraulic modeling software program, from Bentley Systems [15]. With the use of WaterCAD scenario management tool, different leakage scenarios were created. In these scenarios the location and diameter of pressure reducing valves (PRVs) were altered. Leakage variations due to these scenarios will be observed so that any relationship between both PRV location and Leakage rate can be evaluated.

2. Material and methods

2.1. Study area

The study area is Arama district measured area (DMA) in Alexandria, Egypt (Fig. 1a). Arama is located between coordinates 31°15′44.23″ North and 30°0′52.85″ East. The configuration of this study consists of a pipe network with 4800 inhabitants (210 l/inhabitant/day) and 177 main service connections, 1200 sub-service connections. The network has lengths of approximately 1.03 km. Arama DMA consists of 37 Asbestos pipes and 25 junctions. In the pilot area Arama, all consumers are measured and billed. The unbilled authorized consumption is zero. The area is fed from 6 inlet pipes, 5 of them have been closed so that now it is fed by Just one inlet 12 in. PVC pipe (Fig. 1b). An ultra-sonic flow meter was used at the inlet of DMA to measure the input flow. Seven

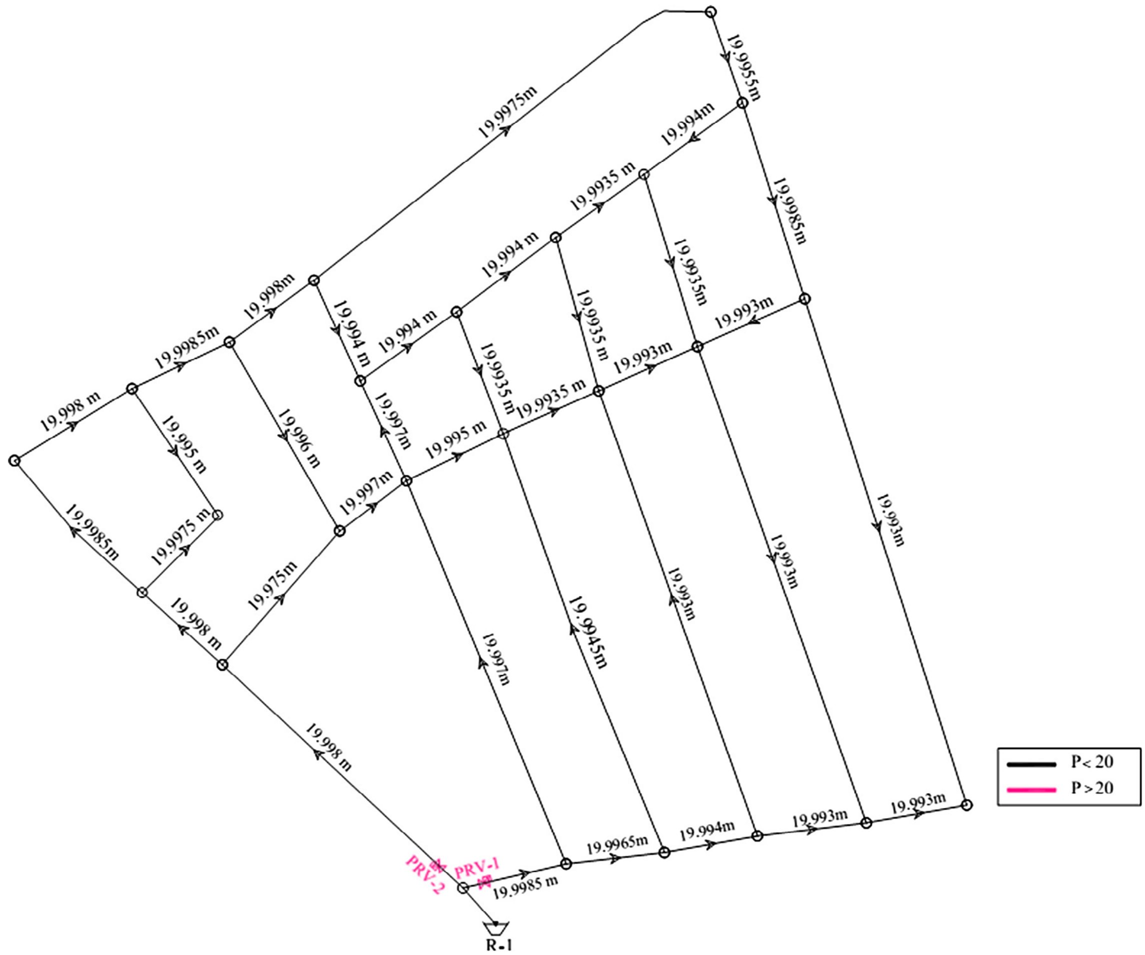

Fig. 3b The first scenario.

valves were used to isolate the DMA and control the input flow and the pressure. The losses were calculated before and after the replacement of non-working meters in the pilot DMA. The losses in the pilot DMA were reduced from 54% to 23% of the input volume just after replacing 44 old and stopped meters [14].

2.2. Performance indicators for physical losses

2.2.1. The infrastructure leakage index (ILI)

The International Water Association (IWA) has developed an infrastructure leakage index (ILI). It is recommended by Environmental Protection Agency (EPA), American Water Works Association (AWWA), and International Water Association (IWA) [7].

The ILI is defined as the current annual real losses (CARL) divided by the unavoidable annual real losses (UARL) [5].

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

where CARL is the current annual real losses and unavoidable background leakage rate (UARL) is the lowest technically achievable annual real losses for a well-maintained and well-managed system [8].

In the most basic form, UARL in litres/day is [7]:

$$UARL = (A * L_m + B * N_c + C * L_p) * P$$

where L_m is mains length in km, N_c is number of service connections, L_p is the total length in km of underground pipe between the edge of the street and customer meters, and P is the average operating pressure in meters, and A, B, C are constants and equal to 18, 0.8, 25, respectively [7].

Once the ILI is defined, it can be compared to the expected level of real losses with the assessment matrix for the real losses suggested by the World Bank Institute. This matrix has the real losses in litre/connection/day in different pressure levels [3]. The matrix is divided into two groups; the developed and developing countries (Table 1) [16]. The reason of split is the gap in performance between water utilities in developing and developed countries [3].

- Category A: Good. Further loss reduction may be uneconomic and careful analysis needed to identify cost-effective improvements.
- Category B: Potential for marked improvements. Consider pressure management, better active leakage control, and better maintenance.
- Category C: Poor. Tolerable only if water is plentiful and cheap, and even then intensify NRW reduction efforts.

Fig. 3c The second scenario.

- Category D: Bad. The utility is using resources inefficiently and NRW reduction programmers are imperative.

2.3. Hydraulic simulation and leakage calculation method

The Arama DMA was analyzed using Water CAD, Version 8 hydraulic modeling software program. To simulate real world condition Arama DMA (Fig. 2), all pipes were set to be Asbestos with a Hazen-Williams coefficient of 130. Diameter, length and material of pipes were set as shown in (Table 2), the demand and elevation of each junction were set as revealed in (Table 3).

The network simulation software must satisfy three basic principles to determine pressure and balance the flow within the model, mass balance, energy balance, and flow and head loss must be consistent with the appropriate velocity-head loss equation [15,17].

With the use of scenario management tool in WaterCAD, different leakage scenarios were created [18]. PRVs are instruments that are installed at strategic points in the network to minimize the quantity of leakage by reducing pressure. PRVs maintain the pre-set downstream pressure regardless of the upstream pressure. Valves are usually sited within a district metered area (DMA), they should be downstream of the flow meter so that turbulence from the valve does not affect the accuracy of the meter [2].

The diameter and location of PRVs were altered in the different scenarios. PRVs in all scenarios were set up to constant pressure 20 m. Leakage variations due to these scenarios were observed so that any relationship between both PRVs location and Leakage rate can be evaluated.

Base scenario: the pressure reduction valves weren't used in this scenario. The pressure was monitored and real losses were calculated to compare it with the real losses which calculated from the other scenarios,

First scenario: PRV with diameter 6 in. was installed on pipe (P-1) and PRV with diameter 12 in. was installed on pipe (P-6), the diameter of PRV should be as same as the diameter of pipe which it was established on, but in case there was used PRV with diameter less than the diameter of pipe we must check the velocity.

Second scenario: 2 PRVs were set on pipes (P-1) and (P-7) respectively, with diameter 6 in.

Third scenario PRV was installed on pipe (P-1) with diameter 6 in. and PRV was set on pipe (P-34) with diameter 12 in.

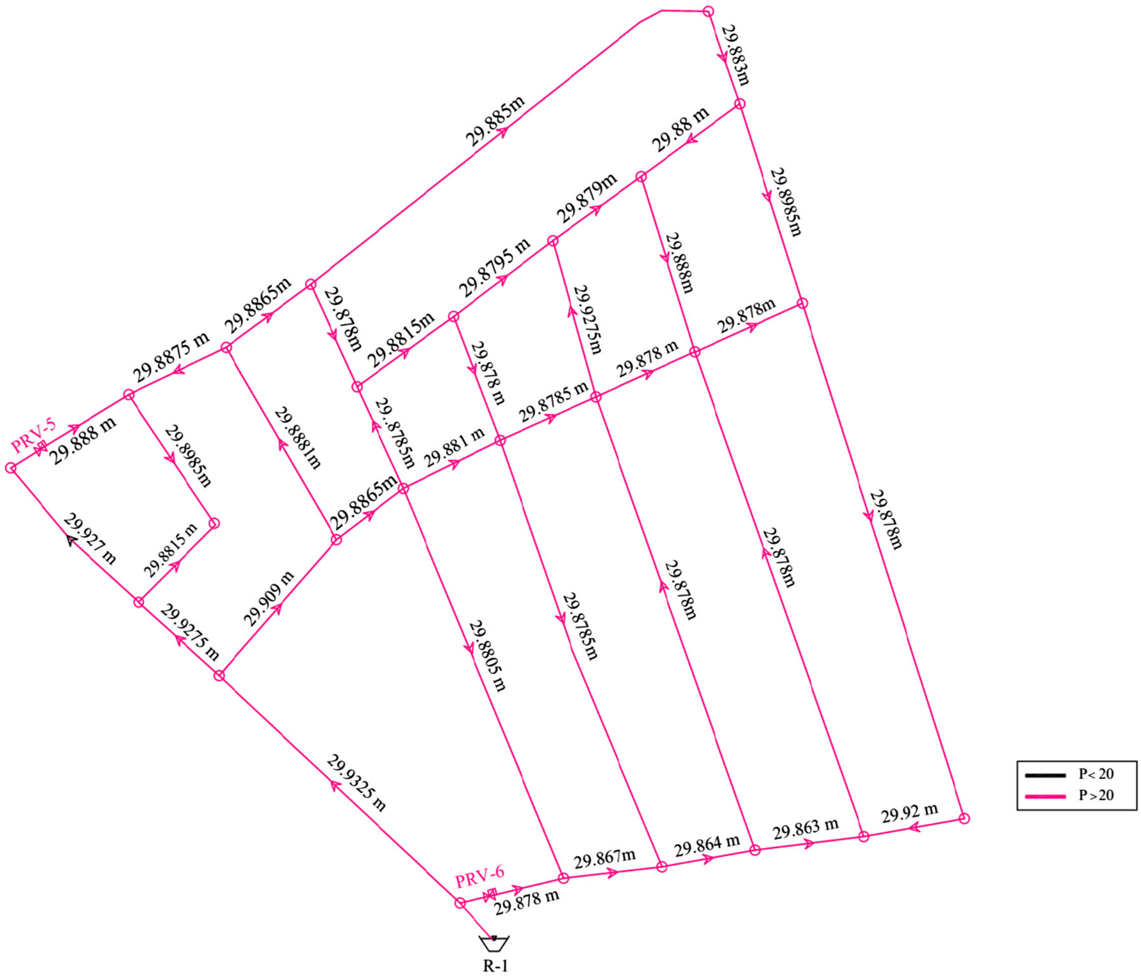

Fig. 3d The third scenario.

Fourth scenario 3PRVs were established on pipes (P-1), (P-12) and (P-18) respectively with diameter 6, 6 and 12 in. respectively.

Fifth scenario PRV was set on pipe (P-1) with diameter 6 in., PRV was installed on pipe (P-12) with diameter 6 in. and PRV was established on pipe (P-34) with diameter 12 in.

For each scenario, the values of pressure in pipes are used to calculate leakage as,

$$q = \beta P^{\alpha} L$$

where P is the pressure in pipe, L is the pipe length, and α, β: are the leakage model coefficients [19].

β depends, in general, on pipe characteristics, traffic loading, external stress, environmental conditions and corrosion. It is also strongly related to the number of leaks per unit of pipe length. In contrast, α is a function of pipe material and rigidity, it is closely related to the hydraulics of leakage [12,19].

The value of the leakage parameter α can be described using the fixed and variable area discharge (FAVAD) approach. It can be considerably larger than 0.5 and typically varies between 0.5 and 2.79 with a median of 1.15 [19,20]. It was assumed to be 1.2 in this study.

The value of β coefficient for the leakage increase rate can be assumed close to zero in systems where utilities routinely conduct leak repair activities [21]. In order to calibrate β coefficient of the leakage model in this study, the value of α was set to 1.2 and the equation was solved using actual leakage volume in Arama DMA (q_{leak}) equal 23% of total network entry flow (q_{inflow}).

$$q_{leak} = \beta \sum (L_1 P_1^{\alpha} + L_2 P_2^{\alpha} + \cdots + L_{37} P_{37}^{\alpha})$$

The total reduction of leakage volume at the WDN entry point (ΔVL) is given by the difference between the current calculated leakage volume (VL base scenario) and the estimated leakage after pressure reduction (VL scenario).

$$\Delta VL = VL(base\ scenario) - VL(scenario)$$

3. Results and discussions

CARL and UARL are used to calculate the ILI, which was specifically designed to compare technical real losses management between utilities.

The value of CARL was 1345 l/day/connection for Arama district measured area, UARL was 30 l/day/connection and then the value of ILI was 44.8.

Comparing ILI with real losses target matrix, it is noted that, ILI = 44.8 > 16 according to the matrix, the network

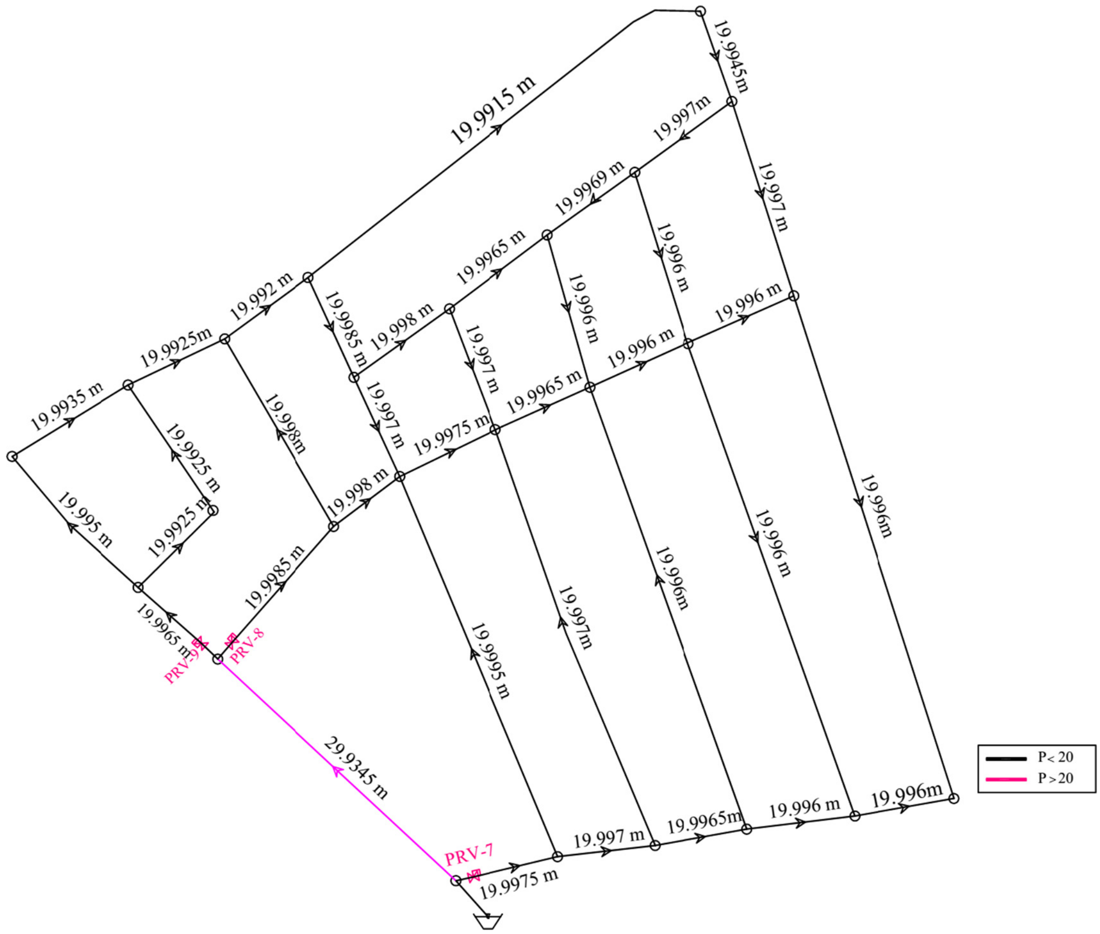

Fig. 3e The fourth scenario.

is on class D which indicates that the utility is using resources inefficiently and NRW reduction programmers are imperative.

The result of β was 2.178 * 10^{-5}. The growth of β is a reasonable estimate for utility without an ongoing leak detection program.

Figs. 3a–3f indicate the pressures in each pipe of the DMA in the base scenario and five scenarios.

The initial flow through the water distribution system measured by ultrasonic at the inlet of DMA, it was 1000 m^3/day.

Base scenario results show that, the leakage through the DMA was 230 m^3/day, the maximum velocity was 0.194 m/s, while the minimum velocity was 0.0055 m/s, the velocities in piping system are very low than the limits of the Egyptian code, this is because the water distribution network was designed to serve the city and its future expansion for long time. The maximum and minimum pressures were 29.935 m and 29.923 m, respectively.

In the first scenario, the average pressure in the DMA dropped to about 19.995 m. The calculated leakage in the DMA after pressure reduction was 142 m^3/day. Comparing with the calculated leakage in the base scenario, the use of PRV in this scenario led to reduce the leakage by 37%.

In the second scenario; the position of the PRVs were not effective, the pressure in the DMA has not decreased significantly. The calculated leakage volume after pressure reduction was 230 m^3/day. There is no change between the leakage volume in base scenario and second scenario.

In the third scenario; the change in leakage volume after reducing pressure was unnoticed. The calculated leakage after pressure reduction was 230 m^3/day.

In the fourth scenario; the locations of the three valves which used in this scenario were very influential. The pressure in the most of network was reduced to about 19.996 m, while in pipe (P-6) the pressure was not reduced. The calculated leakage volume after using PRVs was 146 m^3/day. Significant difference between the calculated leakage quantity in the base scenario and the quantity calculated in the fourth scenario can be seen.

In the fifth scenario; the calculated leakage volume after using PRVs was 228 m^3/day. The pressure reduction in DMA was not affected by the location of PRVs. Therefore the leakage within DMA was slightly decreased.

Table 4 shows, for each scenario, the number and diameter of PRVs, the leakage volume estimated from equation $q = \beta P^{\alpha} L$ and the total reduction of leakage volume ΔVL.

Studying the five scenarios, as shown in (Table 4), the first scenario is the best practice to minimize the quantity of leakage through DMA. It has the least leakage volume, after establishing PRV (1), and PRV (2) the leakage drops from 230 m^3/day to142 m^3/day.

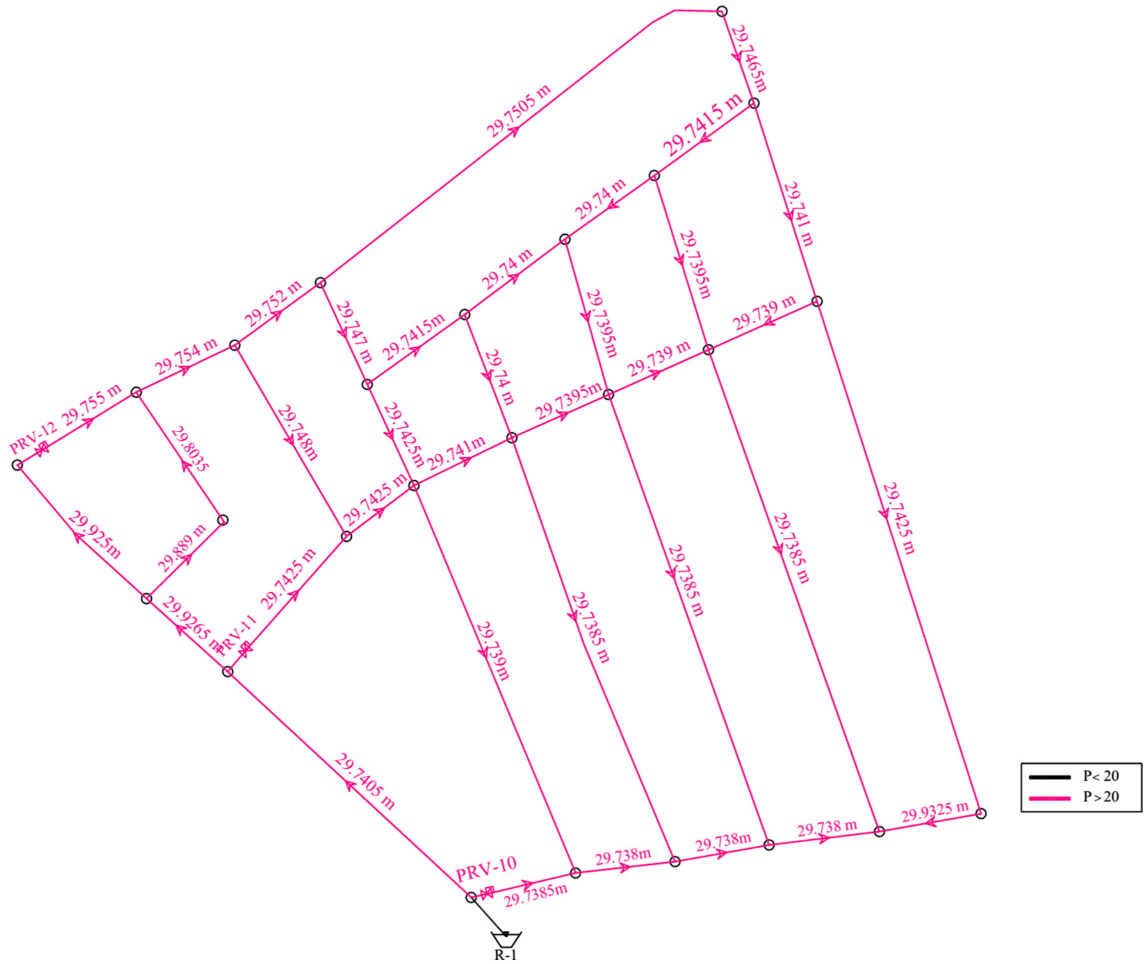

Fig. 3f The fifth scenario.

Table 4 The results of scenarios.

Scenarios	Leak (m^3/day)	PRV			ΔVL (m^3/day)
Base Scenario	230				
Scenario (1)	142	PRV-P1-6inch	PRV-P6-12inch	–	88
Scenario (2)	230	PRV-P1-6inch	PRV-P7-6inch	–	–
Scenario (3)	230	PRV-p1-6inch	PRV-P34-12inch	–	–
Scenario (4)	145	PRV-P1-6inch	PRV-P12-6inch	PRV-P18-12inch	85
Scenario (5)	228	PRV-P1-6inch	PRV-P12-6inch	PRV-P34-12inch	2

4. Conclusions

- The WaterCAD hydraulic simulation program is used to run different leakage scenarios by introducing the pressure on each pipe, and supporting decision systems regarding the quantification and location of pressure reduction valves.
- Infrastructure leakage index (ILI) showed its performance in evaluating the network and its need to leakage reduction.
- Pressure management, using the pressure reduction valves, is an effective way to control the amount of leakage in water distribution system (WDS).
- The leakage volume through Arama DMA dropped by 37% after pressure reduction.
- This approach can be extended to other DMA throughout Egypt with similar characteristics, and to other regions through collection of network and leakage data.

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