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Leakage–pressure relationship and leakage detection in intermittent water distribution systems

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ABSTRACT

Field investigations were conducted to identify the relationship between leakage rate and pressure in selected areas of the water distribution system of the Holy City of Makkah, Saudi Arabia. Noise correlators were used to detect leaks in areas where the water leakage exceeded 20% of the total water supplied. The leakage rate was found to be related to pressure raised to the *n*th power. The value of *n* was found to be 0.50 for the network of asbestos-cement pipes and 1.16 for the network of mixed pipes. Considering the age of the network, the leakage rate was found to be linearly related to the age of the network and related to pressure raised to the 1.10 power. About 63.15% of the leaks were found to be at the property connections. The rest were either in the service lines or at the junction of the service lines with the property connections. The galvanized iron property connections were found to be highly corroded, with circular holes and/or longitudinal corrosion cracks.

Key words | leak detection, leak localizing, leakage, water distribution network, water losses

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INTRODUCTION

The scarcity of potable water in dry climate countries such as Saudi Arabia and the relatively high cost of producing fresh water from desalination plants have placed an obligation on the water authorities to search for cost-effective techniques to optimize the available water resources and reduce the losses. Studies in different parts of the world show that the amount of unaccounted for water (UFW) in Water Development Authorities (WDAs) ranges from 5 to 45% (Al-Ghamdi 2005; Al-Ghamdi & Gutub 2000). UFW is defined as the water supplied to a system that does not generate revenue or does not reach the customer (Myers & Lambert 1998). UFW comprises several elements: leakage from the network components and house connections, unmetered connections, illegal connections, erroneous meter readings, water used for flushing the network during maintenance, and unpaid public water use. A considerable amount of UFW is lost in the WDAs due to leakage that can be reduced by adopting an active leakage detection program. A successful program should comprise an effective method for leakage quantification, a powerful technique for locating the leaks, effective operation and maintenance of the network, and proper management of the system pressure.

The amount of leakage depends on a number of factors: pipe age, pipe corrosion, pipe depth, heavy traffic loads, ground movement, pressure surges, improper handling and storage during construction, poor workmanship, damage to the network during installation of other utilities, and operating pressure. Excessive operating pressure is expected to be a major factor in leakage. This is even more profound in intermittent water supply systems, which are found in most water-scarce cities around the world. These networks are usually designed for continuous pumping but very often operate intermittently under unnecessarily high pressure. In such cases, proper management of the operational pressure may considerably reduce the leakage and conserve a valuable natural resource.

This contribution was aimed at highlighting several results of water leakage field investigations conducted in selected districts of the intermittent water distribution system (WDS) serving the Holy City of Makkah, Saudi

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Arabia. The paper focuses on the relationship between leakage rate and operating pressure in the tested areas. It also presents the techniques used for locating the leaks and summarizes the findings of the leak detection survey.

NETWORK DESCRIPTION AND LEAKAGE

The Holy City of Makkah, which is located in the western province of Saudi Arabia, has a total population of about 1.4 million. However, being the capital of the Muslim world, it is visited by millions of people for pilgrimage during the last month of the lunar year and for Omrah throughout the year, especially during the holy month of Ramadan. During these seasons the population of the city exceeds 3 million. The city depends mainly on a desalination plant located on the coast of the Red Sea, about 110 km to the west, for water supply. Desalinated water contributes about 90% of the city's supply and the rest is provided from well fields in the nearby wadis. The water supply from desalination increased during the regular season from 151,250 m^3/d in 2001 to 216,000 m^3/d in 2004. However, in the pilgrimage season the water supply increased from 184,250 m^3/d in 2001 to 248,000 m^3/d in 2004. Due to the water supply shortage, the water authority has adopted water rationing to control water demand. Hence, the city's water distribution network is run on an intermittent basis.

The city has been divided into 240 supply zones and the zones are organized into groups. Water is pumped to a group of zones for a prescribed number of days and then switched to the next group. The pumping schedule varies considerably throughout the year and in many cases water is supplied through the network once every 17–30 days. Each property is equipped with an underground storage tank and an overhead tank. If a property's water demand is high or the underground storage tank does not supply enough water during the nonpumping period, consumers buy additional water from water suppliers equipped with water tankers. The frequency of water supply to each zone increased considerably after the operation of a new desalination plant commenced in 2009. Al-Ghamdi (2002) provided a detailed description of the water distribution network serving the city.

Al-Ghamdi & Gutub (2002a, b, c) conducted a rigorous leakage study on seven representative districts of the city using the pressure test method and found that the leakage in these areas ranges from 6.22 to 56.24% with an average value of 31.62%. Details of the studied areas are presented in Table 1.

Pressure effect on leakage

There is a physical relationship between leakage rate and pressure. This relationship can be expressed in the general form of the orifice equation:

$$Q = a P^n \tag{1}$$

where Q is the leakage rate (L/s), and P is the pressure (bar). The coefficient a and exponent n are constants determined from the field investigations.

The theoretical value of n for orifice flow is 0.5, but field studies show that the value varies considerably. For large WDSs with mixed pipe materials, the relationship between Q and P can be assumed to be linear, i.e. $n = 1.0$. For

Table 1 | Characteristics of the studied areas

Area no.	Study area name	Area (m^2)	No. of property connections	Total pipe length (m)	Connections (km^2)	Year of construction	Leakage (%)	Leakage (L/min/ connection)	Leakage (L/min/km)
1	Kuday	500,000	164	6673	328	1994	6.22	0.702	17.26
2	Aziziah	310,000	236	5048	761	1992	12.60	1.446	67.51
3	Al-Hindawiah	218,000	142	3563	651	1979	32.09	3	119.56
4	Jarwal	200,000	160	2706	800	1979	56.24	3.21	189.80
5	Al-Misfalah	32,000	163	1029	5094	1978	50.73	2.316	366.76
6	Al-Taneem	340,000	162	5726	477	1990	17.58	1.584	17.58
7	Ajiad	40,000	151	1340	3775	1979	45.89	1.554	45.89

WDSs with plastic pipes, the leakage rate is approximately related to the pressure raised to the 1.5 power. For metal pipe systems, in which leakage is predominantly due to pipe breakage, the orifice equation can be applied with $n = 0.5$. Greyvenstein & van Zyl (2005) conducted a number of experiments with various pipe materials and found that the leakage exponent has the following ranges: asbestos-cement pipe with longitudinal crack ($n = 0.78$–1.04), steel pipe with corrosion cluster ($n = 1.90$–2.30), steel and unplasticized polyvinyl chloride (uPVC) pipe with round hole ($n = 0.52$–0.53), uPVC pipe with longitudinal crack ($n = 1.50$–1.85), and uPVC pipe with circumferential crack ($n = 0.40$–0.52). Shammas & Al-Dowailia (1993) and Sendil & Al-Dowailia (1992) found that the value of n varies from 0.66 to 1.26 for the WDS in Riyadh, Saudi Arabia. It can be concluded that the exponent value depends mainly on the shape of the crack. Round holes will simulate orifice flow with $n = 0.5$, while longitudinal cracks exhibit a higher value of n.

To determine the relationship between leakage rate and pressure in the water distribution network of the Holy City of Makkah, two of the seven studied areas (Area 2 and Area 3) were tested at different pressures. The network in Area 2 consists of uPVC pipes (76.5%) and ductile iron pipes (23.5%), while the pipe material in Area 3 is solely asbestos-cement. Pipe materials for the areas tested are presented in Table 2.

The pressure test was performed on the areas during the nonpumping period by plugging all the property connections at each service meter and adjusting the inlet pressure to the study zone with valves and pumps. As some property connection valves may have leaked, leading to a false leakage rate, property connections were plugged instead of just closing the valves. The tests were conducted according to widely practiced procedures for field pressure testing found in the literature (e.g. Al-Dhowalia *et al.* 1992; Al-Ghamdi & Gutub 2000). The inflow to the test area was measured with a clamp-on, transit time ultrasonic flow meter. The ultrasonic flow meter has an accuracy of ±0.5% and is equipped with a data logger that can record the flow variation with time for any specific time interval and time increment. The pressure in the feed line was measured using a regular Bourdon tube pressure gauge. Both the flow meter and pressure gauge were calibrated in the laboratory and rechecked regularly to ensure accuracy and correct deviations in the readings.

Table 2 | Pipe materials in pressure tested areas

Area no.	Pipe diameter (mm)	Pipe material Ductile iron	uPVC	Asbestos-cement	Total length (m)
2	80	735	797	–	
	100	63	1955	–	5048
	150	390	1108	–	
3	60	–	–	1488	3563
	80	–	–	2075	

Figure 1 presents the variation of leakage rate with pressure for the two studied areas. The leakage rate equations that resulted from curve fitting the data for the two areas were as follows:

$$\text{For combined pipes (Area 2):} \quad Q = 0.3182\,P^{1.16} \quad (\text{with } R^2 = 0.81) \tag{2}$$

$$\text{For asbestos pipes (Area 3):} \quad Q = 2.707\,P^{0.50} \quad (\text{with } R^2 = 0.95) \tag{3}$$

where Q is the leakage rate (L/s), and P is the pressure (bar).

From the above equations, it was evident that asbestos-cement pipes exhibited a performance similar to that of metal pipes, for which the leakage rate is related to the pressure raised to the power of 0.5. For the combined pipes of Area 2, the leakage rate was found to be related

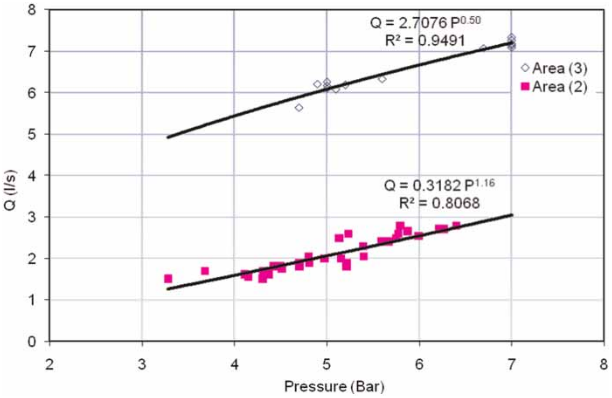

Figure 1 | Leakage rate–pressure relationship for Areas 2 and 3.

to the pressure raised to the 1.16 power, which is in agreement with previous studies.

As pointed out in the introduction, the leakage rate theoretically depends on a number of factors. However, in most cities the major independent variables are most likely the operating pressure, the pipe material and the age of the network. The other variables can be considered insignificant.

Area 3 exhibited a higher leakage rate for the same pressure when compared with Area 2. This can be attributed mainly to the older age of the network in the area compared with the network in Area 2. The data for the two areas can be merged if the age of the network is taken into consideration. It was expected that the leakage rate would increase with the age of the network, especially if maintenance was not adequate. When the leakage rate was divided by the network age N (where N is the network age in years divided by 10) and plotted against pressure, as depicted in Figure 2, the data from the two areas merged into a single correlation as follows:

$$Q = 0.411\,N\,P^{1.10} \quad (\text{with } R^2 = 0.77) \tag{4}$$

where Q is the leakage rate (L/s), N is the pipe age in years/10, and P is the pressure (bar).

Locating leaks

The location of a leak can be identified by different techniques. Visual inspection is probably the easiest and least expensive technique. For example, settlement of soil, pavement or sidewalks may be an indication of a leaking pipe underneath. Similarly, soil wetness or vegetation in a usually dry area is an indication of a water leak. A sudden drop in water pressure and/or flow in the pipeline may be the result of breaks in the line. However, visual inspection cannot detect hidden leaks, especially in sandy soils where the leaking water percolates down through the soil. Leaking water can also go unnoticed by seeping into nearby water bodies or sewer lines. Fortunately, water leaking from pipes creates a distinct noise in the frequency range of 20–1000 Hz (Al-Dhowalia 1992; Hunaidi 2000). The sound waves travel along the pipeline and across the soil layer surrounding the pipe. High frequency sound waves may be detected by human ears or by sounding rods, while the medium and low frequency waves can only be detected by acoustic listening devices.

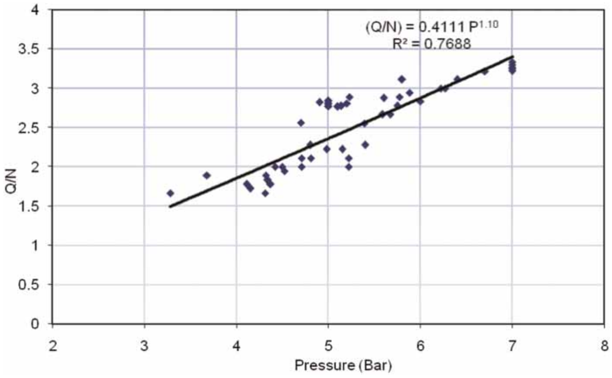

Figure 2 | Leakage rate–pressure relationship for Areas 2 and 3, taking into account the age of the network.

The advanced acoustic listening devices are equipped with geophones, an amplifier and frequency filters to reduce background noise. A technician traces the pipeline by moving the geophone on the ground surface above the buried pipe. They listen for leak noises through their headphones and watch the noise signal on the screen of the acoustic device. The location of the leak can be identified by an intense noise. Use of the acoustic device requires a highly skilled technician and cannot be used in areas where the background noise is high. These devices also fail to detect low frequency leaks or leaks in deeply buried pipes. A more powerful technique to locate leaks in buried pipes employs leak noise correlators. Noise correlators work on the principle that sound waves generated by the leak travel up and downstream of the leak at a predictable speed that depends on the pipe material and diameter. By placing two sensors in contact with the pipe on each side of a leak (placed at valves or fire hydrants) the sound wave travel time up and downstream of the leak can be measured. Consequently, the distance from the leak to the sensors can be calculated. Leak noise correlators overcome most of the limitations of the acoustic listening devices.

Areas with leaks exceeding 20% of the total water supplied, i.e. Areas 3, 4, 5, and 7, were surveyed using acoustic instruments to locate leaks and to undertake needed repairs. Two types of acoustic equipment were used. The first one was an acoustic listening device manufactured by FUJI TECOM INC. (model HG-10AII), while the second was a noise correlator manufactured by Palmer

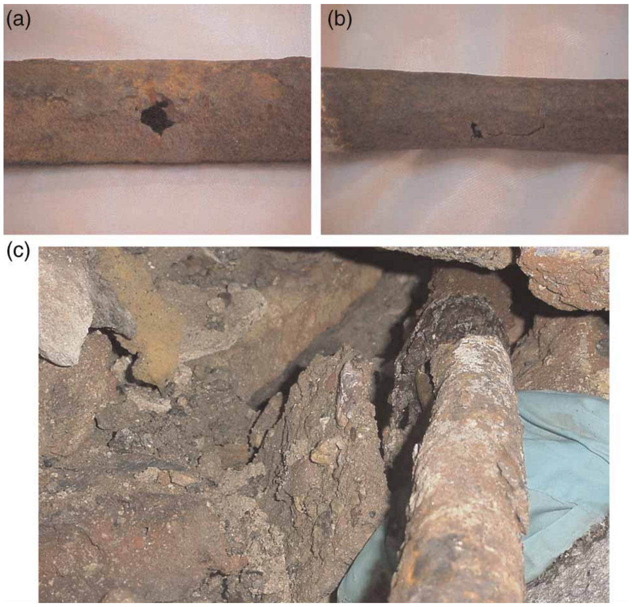

Figure 3 | Holes and longitudinal cracks in corroded property connections: (a) longitudinal cracks; (b) corrosion holes; (c) general view.

Environmental Ltd. under the commercial name MicroCorr 6. Due to the very special nature of the Holy City of Makkah, which inspires continuous movement of people and vehicles, especially in the central area surrounding the Grand Holy Mosque, the ability of the acoustic listening device to locate the leaks was limited by the background noise generated by the traffic. The noise correlator was found to be more appropriate and more reliable in the highly crowded and noisy central area (Al-Ghamdi & Gutub 2002c).

Several leaks were detected in the surveyed areas by using the correlator on both the main pipelines and at the house connections. The number of leaks identified in the four areas is summarized in Table 3. It is clear from the table that 63.15% of the leaks occurred at the house connections. The house connections in these areas were made from galvanized iron. Upon removal for replacement they were found to be highly corroded, with circular holes and/or longitudinal corrosion cracks, as shown in Figure 3. It is also shown in Table 3 that leaks occurred along the pipeline at a frequency of 1.40–4.86 leaks per kilometer of pipe with an average value of 3.08 leaks per kilometer. When related to the number of house connections, the leak frequency ranged from 1.99 to 3.75 leaks per connection, with an average value of 2.68 leaks per connection.

By comparison, Mills (1990) found that in the WDS in Pinetown, South Africa, 21% of the leaks were found at the house connections. In contrast, Lijima (1992) found that 95.9% of the leaks in Tokyo, Japan, occurred at the service connections. This variation may be attributed to the materials used in construction of the connections and the way they were connected to the submains.

CONCLUSION AND RECOMMENDATIONS

The field study was conducted to investigate the leakage rate relationship with pressure and to locate leaks in areas where the leakage was found to be more than 20% of the total water supplied. Pressure tests were performed in two of the seven areas (Area 2 and Area 3) that were studied previously to quantify leakage rates. The network in Area 2 consisted of uPVC pipes (76.5%) and ductile iron pipes (23.5%), while the pipe material in Area 3 was solely asbestos-cement. The network in Area 3 is 13 years older than the network in Area 2. The leakage rate (L/s) was

Table 3 | Summary of leaks identified by the noise correlator

Area no.	Study area name	No. of property connections	Total pipe length (m)	No. of leaks in lines	No. of leaks in connections	Total no. of leaks	Leaks per 100 connections	Leaks per km of lines
3	Al-Hindawiah	142	3563	3	2	5	3.52	1.4
4	Jarwal	160	2706	3	3	6	3.75	2.22
5	Al-Misfalah	163	1029	1	4	5	3.07	4.86
7	Ajiad	151	1340	0	3	3	1.99	2.24
Ave.	–	–	–	–	–	–	3.08	2.68
Total	–	–	–	7	12	19	–	–

found to be related to the pressure (bar) raised to the nth power. The value of the exponent n was found to be 0.50 for the asbestos-cement pipe network and 1.16 for the mixed pipe network. The data for the two areas merged into a single correlation with $n = 1.10$ when the age of the network was taken into consideration.

The areas with leakage above 20% of the total water supplied were surveyed with a state-of-the-art noise correlator. A total of 19 leaks were identified and repaired. About 63.15% of the leaks were found to be at the property connections and the rest were either in the service lines or at the junction of the service lines and the property connections. The house connections, which were manufactured from galvanized iron, were found to be highly corroded, with circular holes and/or longitudinal corrosion cracks.

Considering the water scarcity in the Holy City of Makkah and the high cost of water, an extensive leakage detection program is necessary to reduce the leakage in the network, which could reduce leakage to less than 7%. A potential reduction in leakage can be achieved initially by lowering the excessive operating pressures to more practical values. Additionally, the water authority should initiate an extensive, active leak detection program to survey the network on a regular basis using sounding techniques and noise correlation methods to locate leaks, and take necessary corrective actions. Further, the galvanized house connections have been corroding and need to be replaced with connections that will not corrode, such as polyvinyl chloride (PVC) or polyethylene (PE) pipe.

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