Estimation of leakage in the water distribution network of the Holy City of Makkah

Abdullah S. Al-Ghamdi and Saud A. Gutub

ABSTRACT

An investigation into leakage from the water distribution network of the Holy City of Makkah is presented in this paper. Makkah city is located on the western region of Saudi Arabia between latitudes 20° and 22° and longitudes 40° 30′ and 39° 20′. It has a total population of about 1.2 million. The population more than doubles during pilgrimage season. The total length of the water distribution network serving the city is about 2,400 km and has around 65,515 property connections serving nearly 70% of the inhabited areas. The city water network works intermittently and over 24% of the property connections are un-metered; hence, the pressure test method was found to be the best method to quantify the leakage. Seven representative areas with property connections ranging from 142 to 236 connections per area were selected for the field investigations. It was found that leakage in the studied areas ranged from 6.22 to 56.24% with an average value for all areas of 31.62%. The old parts of the network experienced high leakage rates ranging from 32.09 to 56.24% with an average value of 46.24%, while the newer areas demonstrated a reasonable range of 6.22 to 17.58% with an average value of 12.13%.

Key words | intermittent water supply, leakage, water distribution network, water losses

Abdullah S. Al-Ghamdi (corresponding author)
Saud A. Gutub
Civil Engineering Department,
King Abdulaziz University,
PO Box 80204,
Jeddah 21589,
Saudi Arabia
E-mail: *alghamdi@kaau.edu.sa*

INTRODUCTION

The Holy City of Makkah is located in the western province of Saudi Arabia. It has a total population of about 1.2 million. However, as it is the capital of the Muslim world, millions of people visit the holy city for pilgrimage at the end of the lunar year, and for Omrah throughout the year especially during the holy month of Ramadan.

Currently the water supply to the city totals 151,250 m^3 day^{-1} during regular days of the year and reaches about 184,250 m^3 day^{-1} during the pilgrimage season. About 80% of the water supply comes from the desalination plant located some 110 km away on the Red Sea coast while the rest comes from the well fields located in the valleys surrounding the city. The master plan for the city estimated the water demand for permanent residents in 1998 to be 275 l per capita day^{-1} while the water demand for pilgrims was estimated to be 75 l per pilgrim day^{-1}. The master plan expected the residential water demand in 2020 to reach 300 l per capita day^{-1} and the pilgrimage demand to reach 100 l per pilgrim day^{-1}. The current water supply presents only about 52% of the actual demand during off-peak days of the year and declines to only about 47% of the actual demand during the peak (pilgrimage and Ramadan) season. A new desalination plant with a capacity of 378,000 m^3 day^{-1} adjacent to the old plant is under construction. This new desalination plant will supply water to the three major cities in the western region of Saudi Arabia: Jeddah, Makkah and Taif. It has been decided that 60% of this water will be supplied to Jeddah and 40% will be directed to Makkah and Taif. The Makkah share of this water has not been decided yet. The plant is expected to be fully operational before the end of 2002.

Due to the severe shortage in water supply, the Water and Sewerage Authority of the Makkah province (WASA) has adopted the water rationing method for water supply.

Hence, the water distribution network of the Holy City of Makkah is run on an intermittent basis. The city has been divided into 240 supply zones and the water is pumped to a batch of zones for a certain number of days, pumped to another batch on other days and so on. Each property is equipped with an underground storage tank and overhead tank. The water comes from the network once every 17 to 21 days and is stored in the property's underground storage tank, then pumped to the overhead tank to supply water to the property. If the demand inside the property is high or the size of the underground tank is not sufficient to store the water needed during the no-pumping period, the consumers buy additional water from water suppliers using water tankers.

Due to the scarcity and the relatively high cost of water, it becomes essential to take all the necessary measures to conserve water. Leakage quantification and pinpointing of leaks has become an effective tool to reduce losses from public water networks. This study aimed to quantify the leakage in the Holy City of Makkah as a first step to gain control over the leakage problem.

WATER DISTRIBUTION SYSTEM FOR THE HOLY CITY

The total length of the water distribution network serving the Holy City of Makkah is about 2,400 km and has around 65,515 property connections serving nearly 70% of the inhabited areas. Approximately 24% of the property connections are un-metered. Owing to the adverse topography of the city (the city elevations vary from 280 to 700 m above mean sea level), the network is equipped with 50 service reservoirs with a capacity ranging from 3,000 m^3 to 1 million m^3. To supply water to higher locations in the mountains, the network is equipped with about 90 pumps and booster pumps. The pumps' flow rates range from 3 $m^3\,h^{-1}$ to 1,000 $m^3\,h^{-1}$ and they provide a pressure head in the range of 17.5 to 138 m. The development of the network passed through three distinct stages; the old parts of the city are served by parts of the network which were implemented before 1953. This network is poorly designed and most of the pipes are made of galvanized steel and are of small diameter. This network does not meet the current water demand and is currently being replaced. Another network serving the area surrounding the Grand Holy Mosque was constructed between 1972 and 1980. The main lines in this network are made of asbestos cement while the sub-mains are made of galvanized steel. Networks constructed between 1985 and 1993 serve recent areas on the outskirts of the city. The new networks are made of ductile iron and PVC pipes (Al-Ghamdi 2000).

LEAKAGE ESTIMATION TECHNIQUES

Unaccounted-for water (UFW) is defined as the water supplied to a system that does not generate revenue or does not reach the customer (Myers & Lambert 1998). The UFW is made of several elements: leakage from the network components and consumers' connections, un-metered property connections, illegal connections, meter reading errors, meter errors, water used during operation and maintenance for flushing the lines and tanks, and unpaid public water use. Several factors contribute to the amount of leakage in water distribution networks. These factors may include the following (Al-Dhowalia *et al*. 1992): pipe corrosion, the effect of soil and ground water on the pipe material, depth of the pipes, high pressure and pressure surges, ground movements due to temperature or water content variation, heavy traffic loads, poor storage of pipes before construction, poor workmanship in laying of pipes and property connections, insufficient maintenance, and damage caused by construction by other utilities' construction works.

The amount of leakage from water distribution networks can be expressed in several forms (Myers & Lambert 1998; Lambert 1998). The most common way to present the leakage in a water distribution network is by percentage. The percentage is obtained as the ratio of the lost water to the amount of water coming to the network. This method of describing the losses is not acceptable to some researchers because it ignores important factors such as pipe length, the number of property connections, water consumption and mean pressure. Thus, it cannot be

Table 1 | Water losses in some cities around the world

City (country)	Leakage (%)	Year	Reference
Singapore	11.2	1988	Sai (1992)
Singapore	7.7	1991	Sai (1992)
Pine Town (South Africa)	16	1973	Mills (1990)
Pine Town (South Africa)	5	1987	Mills (1990)
Riyadh (Saudi Arabia)	30.4	1991	Al-Dhowalia *et al.* (1992)
Santa Cruise (Bolivia)	30*	1995	Myers and Lambert (1998)
Amman (Jordan)	45*	1987	Myers and Lambert (1998)
Munich (Germany)	23	1986	Al-Dhowalia *et al.* (1992)
Stockholm (Sweden)	29	–	Al-Dhowalia *et al.* (1992)
Los Angeles (USA)	7	–	Victorian Auditor General (1997)
Detroit (USA)	18*	–	Victorian Auditor General (1997)
Anglian Water Services (UK)	14*	–	Victorian Auditor General (1997)
Yorkshire (UK)	22*		Victorian Auditor General (1997)

*UFW (including leakage and others).

used for comparing different systems. Despite that, it is widely used to indicate the losses in water distribution networks. Table 1 provides a list of water losses in some cities around the world.

There are several methods available to evaluate leakage in water distribution networks. Each method has its own limitations. The most popular methods are the total quantity method (water audit), the total and net night flow method, and the pressure test method.

In the total quantity method, the quantity of UFW is determined by calculating the difference between the total amount of water delivered to the network and the summation of the water quantities consumed by customers. This method gives the total UFW rather than the amount of leakage. This method cannot be used if any of the property connections are un-metered or if the error in meter readings is high.

The total night flow rate method assumes that the minimum flow rate that occurs during late night hours will represent the rate of water loss. This method can be improved by calculating the net minimum flow, which is the difference between the total night flow and the actual consumption at night. This method cannot be applied to intermittent supply systems, because in these systems water will flow from the network into property storage tanks to be used later. Hence, the net night flow does not exist in intermittent distribution systems.

The pressure test method is probably the best method to be used in intermittent supply systems especially when the number of un-metered connections is high or when the accuracy of meters is not satisfactory. In the pressure test method, the city is divided into a number of small, manageable zones and representative zones can be selected to undergo the pressure test. The areas selected

Table 2 | Characteristics of the studied areas

No.	Study area	Area (m^2)	Elevation (m)	No. of property connections	Total pipe length (m)	Connections per km^2	Connections per km of lines	Year of construction
1	Kuday	500,000	279.3–290.7	164	6,673	328	25	1994
2	Aziziah	310,000	298.4–304	236	5,048	761	47	1992
3	Al-Hindawiah	218,000	265	142	3,563	651	40	1979
4	Jarwal	200,000	280–340	160	2,706	800	59	1979
5	Al-Misfalah	32,000	285–310	163	1,029	5094	158	1978
6	Al-Taneem	340,000	280–310	162	5,726	477	28	1990
7	Ajiad	40,000	310–365	151	1,340	3775	113	1979
	Total	1,640,000		1178	26,085			

for pressure testing should be representative of the entire network. The steps that can be followed to select pressure test areas and perform pressure tests on them can be found in the literature (e.g. Al-Dhowalia *et al*. 1992; Al-Ghamdi & Gutub 2000).

RESULTS AND DISCUSSION

Based on the criteria specified in the previous section, seven areas were selected as a representative sample of the entire city. The pressure test was conducted in these areas to quantify the leakage. Table 2 provides a description of the selected areas. The number of property connections in the selected areas ranged from 142 to 236 connections, while the area of the selected zones ranged from 0.032 to 0.5 km^2. The total length of pipes in the selected areas ranged from 1,029 to 6,673 m. Table 2 indicates that the density of the property connections in the older part of the city is very high, with a maximum of 5,094 connections km^{-2} in area no. 5, while it is low in the new districts of the city. Narrow streets characterize the older portions of the city and walkways and houses are closely clustered while the new parts of the city are well designed and houses are spaced properly. The very old part of the network (implemented before 1953) was excluded from the study because a project to replace this network is in progress.

The pressure test procedure was implemented in all areas under consideration. The inflow to each study area was measured by a clamp-on, transit-time, ultrasonic flow meter. Unlike in-line meters, clamp-on flow meters measure the flow without requiring physical insertion. The ultrasonic flow meter was selected over the other types of flow meters because of its high accuracy (0.5% for velocity $>0.30\ m\ s^{-1}$), relatively low cost, ease of use and possible linkage to computer monitoring stations (Trofatter 1994, 1996). The flow meter used in this study was Digiflow 2000 manufactured by Flow Metrix, Inc. and distributed by Polysonic (USA). It is equipped with a data logger and can record the flow variation with time for any specified time interval and time increments. The pressure in the study areas was measured using the regular Bourdon gauge meter. Both flow meter and pressure gauges were calibrated in the laboratory and rechecked regularly to ensure high accuracy and to correct any deviation in the readings.

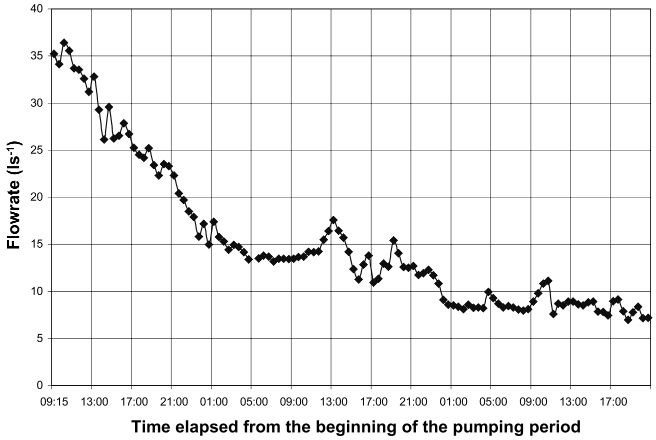

Figure 1 | Water demand at study area 4 during pumping period.

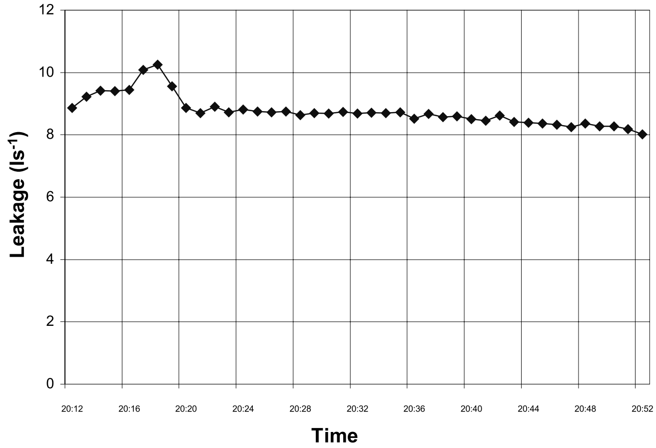

Figure 3 | Leakage in study area 4 during pressure test.

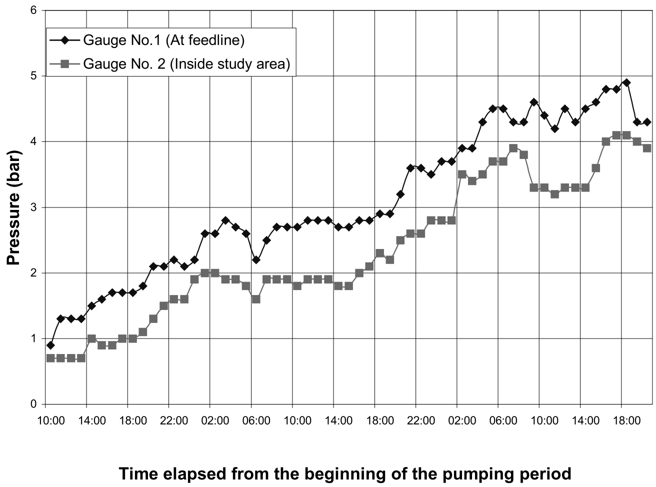

Figure 2 | Pressure variation in study area 4 during pumping period.

A typical inflow during pumping time for area (4) is shown in Figure 1. This figure shows that at the beginning of the pumping period the water demand was high because all the property connections were fully opened to receive water from the network and store it in the underground tanks. As time passed, the water demand decreased as small tanks and tanks in lower areas got full earlier than the other tanks. It would be expected that if the pumping time were extended further, the water demand would resemble the actual water consumption, since all the underground tanks were full and any consumption would be drawn directly from the network.

The pressure variation in the same study area is illustrated in Figure 2. It is clear from this figure that the pressure was initially low due to high flow and, as time passed, pressure increased as property connections closed and reached a maximum value at the end of the pumping period.

The variation of inflow (leakage) for the same study area during the pressure test is shown in Figure 3. The inflow is initially high because some property connections were opened at selected places to bleed out the air from the network. When the inflow reached a nearly steady state for a reasonable period of time, the pressure test was terminated and the leakage rate was calculated as the average of the inflow during the steady state inflow period. The flow and pressure variations in the other study areas exhibited a similar trend as that presented for study area 4.

The results of field investigations and measurements of the seven study areas are summarized in Table 3. It can be noted that the average pressure in the study areas ranged from 2.42 to 7 bar, and that the maximum pressure reached a value of 10.5 bar in area 3. In intermittent water supply systems, high pressure is usually not needed and can be controlled in many cases unless there is a big variation in topography.

The information in Table 3 shows that the amount of losses due to leakage in the study areas ranged from 6.22 to 56.24% with an average value of 31.62%. The relatively new networks (areas 1, 2 and 6) showed an acceptable

Table 3 | Estimated leakage in the study areas

No.	Study area	Minimum pressure (bar)	Maximum pressure (bar)	Average pressure (bar)	Average demand ($l\ s^{-1}$)	Leakage ($l\ s^{-1}$)	%
1	Kuday	0.69	3.52	2.42	30.87	1.92	6.22
2	Aziziah	1.9	3.4	2.48	45.45	5.68	12.6
3	Al-Hindawiah	4.2	10.5	6.95	22.13	7.1	32.09
4	Jarwal	0.9	4.9	3.08	15.22	8.56	56.24
5	Al-Misfalah	3.8	5.7	3.98	12.4	6.29	50.73
6	Al-Taneem	2.8	8.8	4.61	23.98	4.28	17.58
7	Ajiad	1.6	8	7	8.52	3.91	45.89
	Average	2.27	6.40	4.36	22.65	5.39	31.62

level of leakage ranging from 6.22 to 17.58%, with an average value of 12.13%; the older parts of the network (areas 3, 4, 5 and 7) exhibited high leakage ranging from 32.09 to 56.24%, with an average value of 46.24%. It is clear that corrective measures are required to control the high leakage rate in old networks.

CONCLUSION AND RECOMMENDATIONS

The field study was conducted to investigate leakage from the water distribution network of the Holy City of Makkah. Since the network is working intermittently and over 24% of the property connections are un-metered, the pressure test method was found to be the best method to identify the leakage. Seven areas with property connections ranging from 142 to 236 connections per area were selected for the field investigation. It was found that the leakage in the studied areas ranged from 6.22 to 56.24%, with an average value for all the areas of 31.62%. The old parts of the network experienced high leakage rates ranging from 32.09 to 56.24% with an average value of 46.24%, while the recent areas demonstrated a reasonable range of 6.22 to 17.58% with an average value of 12.13%.

It is evident that the water loss due to leakage in the network is exceptionally high especially in the old parts of the network and corrective measures are required to lower the leakage to acceptable limits. Considering the water scarcity in the city and the high cost of water, an extensive leakage detection programme is necessary to reduce the leakage in the network to less than approximately 7%. A reduction in leakage can be achieved initially by lowering the operation pressure to a more practical level. However, the water authority should initiate an extensive leak detection programme to survey the network on a regular basis using sounding techniques and auto correlation methods for pinpointing the leakage and taking the necessary corrective actions.

ACKNOWLEDGEMENTS

The authors wish to thank the Water and Sewage Authority of Makkah Province and Fakiah Research and Development Center for sponsoring this study.

REFERENCES

Al-Dhowalia, K. H., Quraishi, A. A. & Sendil, U. 1992 *Assessment of Leakage in the Riyadh Water Distribution Network*. Final Report, KACST Project No. AR-10-19.

Al-Ghamdi, A. S. & Gutub, S. A. 2000 *Investigation of Leakage from the Water Distribution Network of the Holy City of Makkah. Phase (I): Quantification of Leakage*. Final report, Fakieh Research and Development Center, Makkah, Saudi Arabia.

Lambert, A. 1998 A methodology for National and International Comparison of UFW. *11th IWSA-ASPAC Regional Conference*, pp. 147–152.

Mills, R. E. 1990 Leakage Control in a Universally Metered Distribution System: Pinetown Water's Experience. *J.IWEM* **4**, June, 235–241.

Myers, A. and Lambert, A. 1998 *Effective Leakage Management, Strategic Planning and Operational Control for Water Distribution Networks Using The Bursts and Background Estimates Concepts*. Ministry of Municipalities and Rural Affairs, Saudi Arabia, and The World Bank Workshop on Leakage Management, 2 December 1998, Riyadh, Saudi Arabia.

Sai, F. C. 1992 Water Distribution System Management in Singapore. *Proceedings of American Water Works Association (AWWA) Annual Conference, June 18–22, 1992, Vancouver, B. C.*, 533–552.

Trofatter, J. 1994 Transit-Time Flowmeters Overcome Earlier Limitations. *Wat. Wastewat. Int.*, June, 16–19.

Trofatter, J. 1996 Clamp-on Flowmeters Clamp Down On Leakage. *Wat. Wastewat. Int.*, October.

Victorian Auditor-General's Office 1997 *Report on Ministerial Portfolios*. Victorian Auditor-General's Office, Australia.

First received 26 October 2001; accepted in revised form 20 January 2002