J. King Saud Univ., Vol. 5, *Eng. Sci.* (2), pp. 213–228, Riyadh (A.H. 1413/1993)

Effect of Pressure on Leakage Rate in Water Distribution Networks

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(Received 16/12/1991; Accepted 9/5/1992)

Abstract. A field study was undertaken to provide a means by which the effect of pressure reduction on leakage rates in a water disribution network can be predicted using the results from the experimental program. Nineteen sections covering the water networks in two areas were isolated and each section was pressure tested for quantification of leakage at 1.5, 2.5, 3.5 and 5 bars. The results obtained from this work indicated that pressure reduction is more beneficial for leakage control than what had been predicted by the theoretical orifice relationship. Given such simple methodology for developing a relationship relating leakage rate to operation pressure in a water network, water authorities will be able to take their decisions on pressure reduction as a leakage control measure more objectively.

Introduction

Detailed literature search has shown that various methods of leakage control are being practiced in water distribution systems for different cities and countries. Although there are multi variations in use, yet it is possible to have them grouped into either passive or active control with the latter being categorized into five methods [1-7];

1. Passive control
2. Pressure control
3. Regular sounding
4. District metering
5. Waste metering
6. Combined district and waste metering

In passive leakage control only evident leaks, either due to consumer complaints or due to water appearing on the road surface, are repaired. In active control an organized and systematic program is undertaken in order to detect, locate and repair leaks.

Pressure control method can be considered as a prevention measure. Excessive and unwarranted pressures in certain areas are brought down in order to reduce both incidence rate of pipe failures and rate of water leakage. Sounding method is based on a regular inspection scheme in which listening devices and noise correlators are used to locate leakage throughout the water network. In district and waste metering methods, the water network is divided into areas each being metered on a regular basis. The district metering is based on comparison of water entering the area with the actual metered consumptions. In the case of waste metering method, the leakage is determined by measuring the low rates of flow at night and comparing it with a present standard minimum night flow. The last method is merely a combination of both district and waste metering being practiced simultaneously or in combination.

Selection of Leakage Control Method

In order to be able to select the most suitable and appropriate method of leakage control, it is essential for a water authority to have the information required to estimate the cost and benefit for each of the available alternatives. The cost of each control method can then be compared to the benefit and net saving be determined. The method that yields maximum return is then selected. The National Water Council (NWC) in the United Kingdom has suggested such a procedure for the dcetermination of leakage control policy [1]. A flow diagram summarizing the recommended outline of a scheme starting from measurement of leakage and ending in the implementation of control measures is shown in Fig. 1.

It is granted that the higher the cost of water production, the most becomes the need for extensive and elaborate measures for control. However, the overall yearly cost for lost water is also a function of the amount of leakage. Thus it makes no sense, even if the water is expensive, to go into an extensive and costly control measures if the amount of water losses from the system is low. In other words, before embarking on any leakage control policy it is recommended that where pressure reduction is feasible it needs to be investigated and an assessment of its benefit-cost ratio be made [1,8].

Little information is available in the literature to provide adequate data and reliable information upon which a factual assessment of the economics of pressure control could be made. It is a well known fact that high pressure results in higher rate of leakage in a water network, increases the frequency of leak occurrence, and causes leaks to appear sooner by rendering them easier to locate [1,9]. However, except for

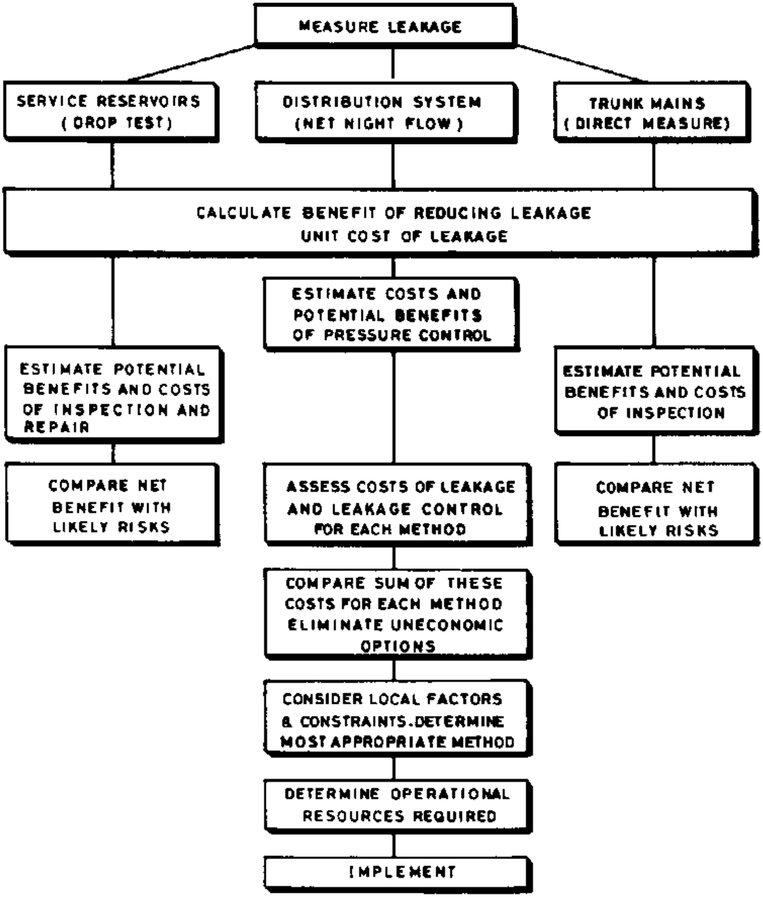

Fig. 1. Flow diagram of the procedure for the determination of the leakage control policy (1)

a very few cases reported from the United Kingdom by the National Water Council [1] and Field [10], only scattered data are available that depict the effect of pressure on leakage rates in water distribution systems. Both NWC and Field found that a significant increase of flow from leaks, by far greater than what is expected according to the orifice relationship, occurred with increasing pressure. In the U.S., the American Water Works Association (AWWA) [2] mentioned similar findings in their report which stated that a specified increase in operation pressure produced a greater increase in leakage. In India, the Indian Water Works Association (IWWA) [3] reported that increasing the water pressure from 1.8 to 3.3 bars resulted in 30% increase in leakage. In South Africa, Van Duuren, *et. al.* [11] found that reducing the pressure in a test area from 10 to 4 bars reduced water wastage by 2.33 times.

To be able to determine the benefits of pressure control for subsequent comparison against the costs, a means for predicting the amount of water saving as a function of pressure reduction in the water distribution network is required. A field study was undertaken in two areas of Riyadh City in which the rates of water leakage in each area and sections thereof were measured and assessed to evaluate their response to pressure variations. The work presented in this publication is part of the comprehensive research project sponsored by King Abdulaziz City for Science and Technology (KACST) for the assessment of leakage in the City of Riyadh, capital of Saudi Arabia.

Equipment and Methods

Study areas and test sections

According to the configuration of study areas, the position of valves and their working condition, each area was subdivided into approximately ten sections. In order to obtain high sensitivity for leaks, to help as an intermediate step in locating the position of leaks, and to accurately quantify the effect of pressure on leakage rates, the size of each test section was limited to around 50 properties with a pipe length of 1 km [12]. In fact, most of the sections were much smaller having an average of 25 properties and a pipe length of 650 m. Plans and stastistics of test sections including size, pipe diameter, pipe length and number of connected properties are shown in Table 1 for Area 1 and Table 2 for Area 2. In both study areas the age of the network is 9 years and all main lines are of PVC while house connections are of high density polyethylene HDPE.

Equipment

Leakage measurements at preset pressure values were made using the setup shown in Fig. 2. The installation consisted of the following: mobil water tank towed on a trailer; pump, for delivering the required amount of water needed to maintain the preset testing pressure in the isolated section; water meter, to measure the flow of water charged into the system; pressure gauge of the indicating type, to monitor and maintain the required test pressure; special T-connection, to replace the property water meter in the meter box; and other miscellaneous items: cutoff valves, non-return valve (NRV), bypass valves, hoses and a stop watch.

Table 1. Statistics of pressure test sections in Area 1

Section	Area m²	Pipe diameter mm	Pipe length m	No. of property connections
1	26,265	100	672	28
2	38,446	100	1,191	54
3	31,487	100	931	45
4	20,986	100	613	35
5	36,414	100	1,059	42
6	18,953	100	574	15
7	10,037	100	287	13
8	23,847	100	969	36
9	29,031	100	868	42
10	43,962	100	1,010	50
Whole area	279,427 (0.28 km²)	103.5*	8,174 (8.17 km)	360

*Weighted average diameter according to length of pipes

Table 2. Statistics of pressure test sections in Area 2

Section	Area m²	Pipe diameter mm		Pipe length m		No. of property connections
1	12,900		100		590	6
2	21,000	(100) (50)	91.9*	(520) (100)	620	13
3	4,800		150		350	2
4	7,500		100		290	5
5	10,000		100		420	8
6	29,100	(100) (50)	94.4*	(635) (80)	715	29
7	21,600		100		470	22
8	16,800	(100) (50)	82.3*	(310) (170)	480	15
9	2,700		150		360	1
Whole area	126,400 (0.13 km²)		104.2*	(4.30 km)	4,295	101

*Weight average diameter according to length of pipes

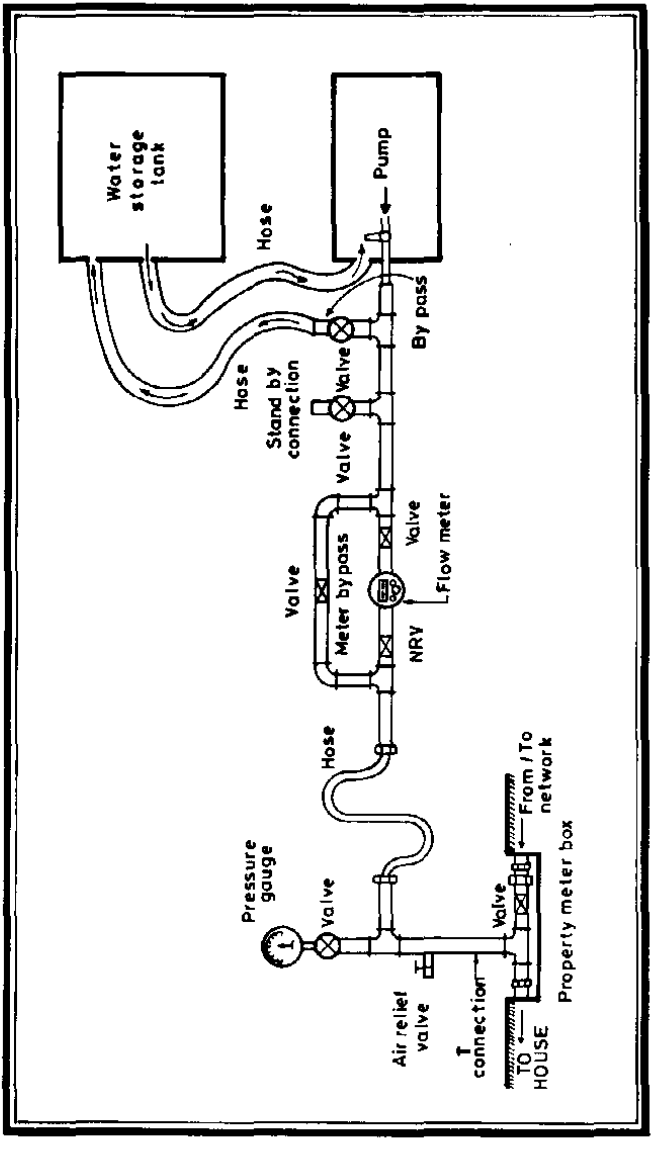

Fig. 2. Schematic diagram of pressure testing installation

Methods

The field pressure test, for leakage quantification in each of the network sections, consisted of the following sequence of operations:

- All boundary isolating valves were closed.
- All stop valves on property connections were closed.
- Testing equipment was assembled at a property meter box.
- The T-connection was placed in the meter box.
- The various components, water tank, pump, flow meter assembly and T-connection were joined by hoses and couplings.
- Flow meter valves was closed and bypass valves were opened (refer to Fig. 2).
- The property meter valve was opened thus allowing a check on whether the section had been completely isolated.
- One of the section isolating valves was opened to refill the pipes and drive air out.
- The pump was put into operation.
- Flow meter valve was re-opened and bypass valves were reclosed.
- Air relief valve was opened and closed several times to assure that all entrapped air was removed.
- The network section was roughly charged to the required pressure by adjusting the pump motor speed. Fine tuning was attained by the manipulation of both flow meter and bypass valves.
- Amount of water needed to maintain the preset steady pressure over a testing period of 10 minutes was recorded and later used for computing the leakage rate through the network section at that specific pressure.
- The last two steps described above were then repeated at three other pressures between 1.5 and 5 bars (the normal range of operation pressure in the city water network).
- All stop valves on property connections were re-opened. If any valve was tampered with i.e. re-opened by consumers, the whole test was repeated in order to avoid false observations and conclusions.
- The T-connection was replaced by the property water meter and the meter box was covered.
- All boundary isolating valves were re-opened and the network section was returned to normal operation.

Results and Discussion

Nineteen sections in Areas 1 and 2 were pressure tested at 1.5, 2.5, 3.5 and 5 bars and the corresponding 76 leakage rates (in liters of water per km of pipe length per mm of pipe diameter per day) were computed from recorded test data. The results are shown in Figs. 3 and 4 for Areas 1 and 2 respectively. The curves for the total areas indicate that an increase in pressure from 1.5 to 5 bars results in 100% increase in leakage levels, from 100 to 207 *l*/km/mm/day in Area 1 and from 152 to 303 l/km/mm/day in Area 2.

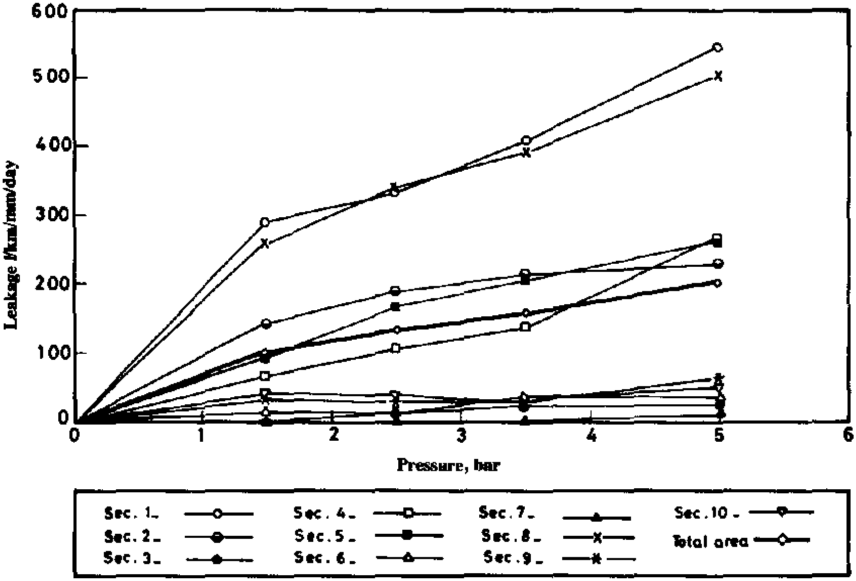

Fig. 3. Effect of pressure on leakage rate in Area 1

It is known that the flow through an orifice, Q is proportional to the square root of the pressure drop across it, P i.e. for an orifice with a proportionality constant, k:

$$Q = k\,p^{0.5} \tag{1}$$

Replacing the theoretical square root value of 0.5 by a general parameter, n, then:

$$Q = k\,p^{n} \tag{2}$$

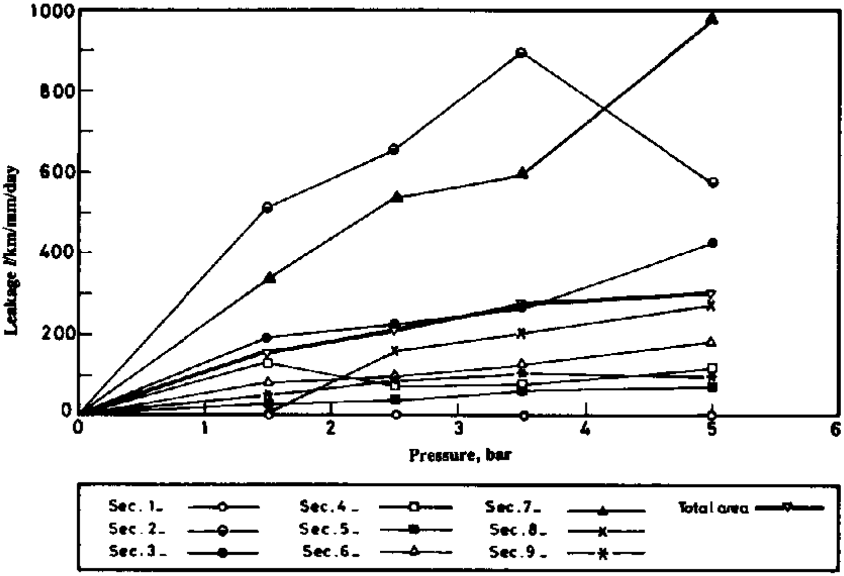

Fig. 4. Effect of pressure on leakage rate in Area 2

Non-linear regression analysis, using a commercially available software, was performed separately for each section and for the whole Areas 1 and 2. In each case, leakage rate was taken as the dependent variable and pressure as the independent variable. The results of the regression analysis are shown in Table 3. Except for the three sections with very low leakage, less than 6% of the water supplied (sections 9 and 10 in Area 1 and section 4 in Area 2 as shown in Table 4) and the single section with very high leakage, greater than 60% of the water supplied (section 2 in Area 2), the correlation between leakage rate and pressure is almost perfect as demonstrated by the high correlation coefficients, especially for the areas as a whole where the correlation coefficients were 0.991 and 0.996. The high leakage in some of the tested sections (section 2 and 7 in area 2) was mainly due to cracked or broked pipes in these sections.

The scatter in the values of k is to be expected since the level of leakage in each of the measured sections is different and does not depend solely upon pressure. However, the value of n is very significant because theoretically, according to the orifice equation, it is supposed to represent the pressure effect.

Table 3. Relationship between leakage rate, Q and presure, P. [$Q = k p^n$]

Section	Area 1			Area 2		
	k	n	r Correlation coefficient	k	n	r Correlation coefficient
1	224	0.52	0.969	*	*	
2	127	0.39	0.979	527	0.19	0.410
3	0.46	2.86	0.925	138	0.62	0.931
4	41.1	1.09	0.980	105	0.09	0.170
5	67.7	0.88	0.985	18.8	0.85	0.957
6	8.42	0.96	0.869	56.5	0.68	0.974
7	*	*	*	235	0.84	0.980
8	208	0.54	0.997	8.23	2.45	0.910
9	23.3	0.46	0.647	43.3	0.58	0.849
10	37.6	0.08	0.202	**	**	**
Total area	77.4	0.60	0.996	123	0.59	0.991

* No detectable leakage (the leakage rate was zero)

** Not applicable (there is no section 10)

The regression analysis (Table 3) shows that the leakage flow does not follow the orifice equation, in which the flow is proportional to the square root of the pressure. The value of n ranging between a low of 0.08 to a high of 2.86, demonstrate that although leakage rate does increase with pressure, yet the effect could be either at a lesser rate or proportionally greater. According to the World Bank [13], this varying impact of pressure on leakage has only recently been appreciated. During the last decade similar experience, especially the fact that small increases in pressure would cause correspondingly greater increase in leakage has been reported by the U.K. National Water Council [1], the American Water Works Association [2] and Field [10]. The discrepancy between the test data and the orifice formula is not completely understood. However, it has been attributed to two probable reasons:

a. Pipe joint, crack or similar opening that either does not leak or exhibits a minor leakage at low pressure may split or widen so that the orifice size increases with pressure [1,2,13].

b. In a water network, there may be many leaks each experiencing a different pressure while the orifice formula applies to a single leak [1].

Table 4. Leakage as percent of water supply* at average operation pressure**

Section	Leakage in %	
	Area 1 Average pressure = 2.5 bars	Area 2 Average pressure = 3.5 bars
1	24	0
2	14	66
3	1	32
4	8	6
5	12	5
6	2	10
7	0	48
8	25	14
9	2	13
10	3	-
Total area	10	22

* The water supply rate was measured over a period of seven days via a mobile water-meter installed on a bypass arrangement on one single feeder main to each isolated area. The average flow was then proportioned among the various sections according to their pipe lenghts.

** The average operation pressure was computed from seven days hourly pressure recordings of two gauges installed at fire hydrants in each area.

Since leakage does not depend on pressure alone, the results from the two study areas have been scaled to show the relative changes in leakage that occur from a pressure change rather than in the absolute terms themselves. In Fig. 5, the vertical scale represents the "leakage factor" which, for this analysis, is defined as the ratio of leakage level at any given pressure to the leakage level at 1 bar for which the leakage factor was taken as unity. In addition to the relationships for the two study areas, the curves representing the orifice equation, the linear relationship and the data reported by the U.K. National Water Council have been plotted in the same manner for comparison purposes. The various curves shown in Fig. 5 indicate that the effect of pressure on leakage rate in the study areas (n values of 0.60 and 0.59), although lower than that of NWC ($n > 1$), it is more significant and steeper than what would have been predicted by the orifice equation ($n = 0.50$). For example, a pressure increase from 1 to 7 bars increases leakage by a factor of 3.2 rather than by 2.6 times according to the theoretical orifice equation, a difference of 23%.

Pressure control is an immediate way of reducing leakage. It is simple and easy to implement at relatively low cost. Pressure reductions can be accomplished by sev-

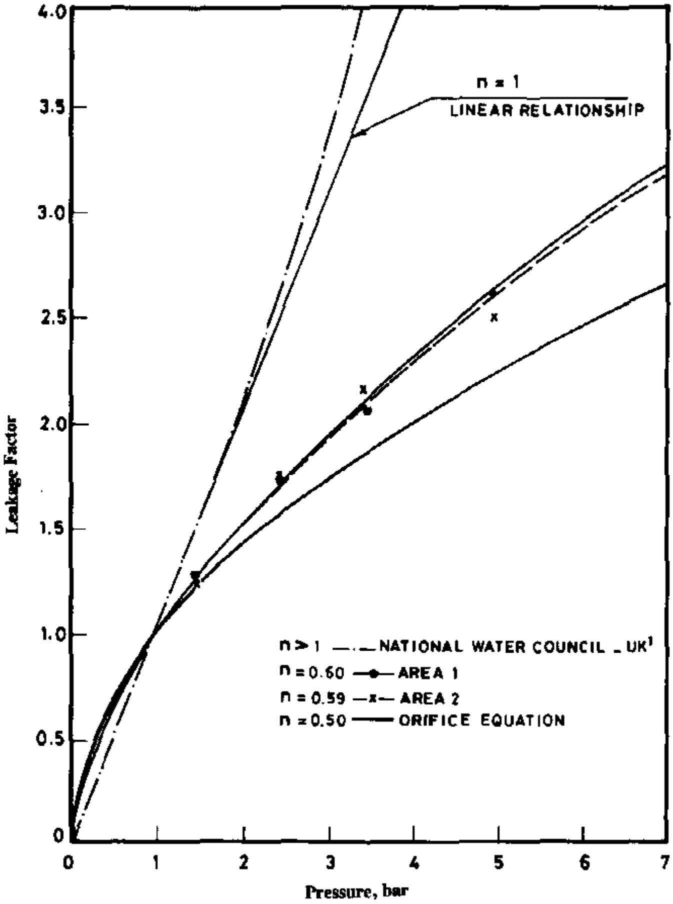

Fig. 5. Relationship between leakage and pressure

eral methods. These include installation of pressure reducing valves, reduction of pumping heads, using break pressure tanks and implementation of pressure zoning by the closer of valves within the water network [1]. The proportionately high reductions in leakage, that can be brought about by relatively milder reductions in a water network operational pressures, further reinforces the potential advantages of pressure reduction as a measure for leakage control, either on its own or in combination with other methods.

Summary and Conclusions

The methodology employed in this study for the development of a relationship between leakage rate and operational pressure in a water supply network proved to be simple and easy to implement. It utilizes inexpensive and readily available equipment to any water supply authority.

The results obtained from this work indicated that pressure reduction is even more beneficial for leakage control than what had been predicted by the theoretical orifice equation. The usefulness of having a relationship that can accurately predict the change in leakage rate that can be induced by a given change in pressure is three folds:

- It is very handy for meaningful comparison of data obtained from various studies and areas.
- It establishes a rigorous basis to convert a measured net night flow into a daily water leakage figure taking into consideration the hourly variations in pressure throughout the day.
- It contributes to the establishment of a rational policy and program for leakage control through its ability to quantify the potential advantages of pressure reduction as a measure for leakage control.

Acknowledgement. This work is part of a research study sponsored and funded by King Abdulaziz City for Science and Technology (KACST) through Grant AR-10-19. The authors thank the Riyadh Region Water and Sanitary Drainage Authority (RRWSDA) for their support, invaluable help and accessibility.

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تأثير الضغط على معدّل التسربات في شبكات المياه

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(استُلم في ١٦/١٢/١٩٩١م؛ قُبل للنشر في ٩/٥/١٩٩٢م)

ملخص البحث. تتناول الورقة دراسة ميدانية لمعرفة تأثير تقليل الضغط على معدّل التسربات في شبكات المياه. جرى اختبار وعزل تسعة عشر جزءًا من شبكة مياه الرياض في منطقتين مختلفتين وتم إجراء اختبارات الضغط لقياس كمية التسربات تحت ضغوط ١,٥، ٢,٥، ٣,٥، ٥ بار. النتائج العملية تشير بأن تأثير تقليل الضغط على نسب التسربات أكبر من النسب المتعارف عليها والمحسوبة من المعادلات النظرية.

إن معرفة العلاقة بين كمية التسربات والضغط التشغيلي في شبكات المياه يؤدي إلى تشجيع الجهات المسئولة على اتخاذ القرارات اللازمة لاستخدام التحكم بالضغط كأحد الوسائل المهمة للسيطرة على كميات التسرب في شبكات المياه.