A Software Tool for Non-Revenue Water Calculations in Urban Water Systems in Conjunction with Hydraulic and GIS Models

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Abstract

This paper introduces a procedure to calculate the non-revenue water in urban water systems. A software is developed to determine the components of apparent and real losses. Identification of these parameters is so important especially in countries with critical water resources situation. Evaluation of the apparent losses components has the same importance as leakage, in countries like Iran which all customers are metered. This paper proposes a methodology to calculate the non-physical part of NRW in detail. The software routine also evaluates the leakage performance indicators based on the IWA terminology. Furthermore, this NRW software can be linked to a hydraulic model to determine the network leakage at each node and pipe, by a revolutionary methodology. In addition, it has the ability of integrating with geographical information systems for further network analyses and linkage of network attribute data with map. The results help the decision makers to select the best scheme for reduction of apparent losses and leakage. Finally, the proposed methodology is applied for NRW calculations in one of the Iranian cities and its advantages are highlighted.

Introduction

Non-Revenue Water (NRW) in a water distribution network, which has been recently introduced by the IWA instead of Unaccounted For Water (UFW) (Farley and Trow, 2003), is defined as the difference between total inflow to the system and total metered and authorized un-metered consumptions. NRW is divided into two parts, apparent and real losses. Apparent losses include human, management and metering errors and lead to consumption of water without charging.

Real losses are some amount of water which is wasted from the network. Real losses are categorized to water losses from reported an unreported bursts, background losses, reservoir leakage and overflow and leakage from valves and pumps. The components of NRW are determined by a field study with investigation of all properties in the study area and all the components of water distribution network (such as reservoir, pumps, valves, pipes, etc.).

A few methodologies have been developed to asses the UFW or NRW in water distribution systems, however most of them just concentrate on the real losses concept, and have no emphasis on the apparent losses, which is so important in most undeveloped and developing countries.

As a pioneer, WRc (1980) published the Report 26 in which a methodology to determine the UFW and leakage was included. After a decade and based on comprehensive summarizing of many case studies, Report 26 was revised by the UK Water Industry (1994). As an output, nine reports were published on leakage management concept. At the same time, some research results were presented to introduce new methodologies and terminologies for better understanding of the leakage components. For instance, Lambert (1994) and May (1994) presented the concepts of bursts and background losses estimation (BABE) and Fixed and Variable Area Discharge (FAVAD), respectively. These two concepts were applied in many countries to resolve the problem, regarding real losses and leakage management.

Several models have been developed to evaluate real losses and leakage management schemes, which mostly investigate the leakage calculation, pressure management, optimal leakage level, etc. A list of these models can be obtained from Asadiani (2004). Recently a few software for leakage modeling have been developed which are described as follows.

SANFLOW model (Mackenzie, 1999) uses the Minimum Night Flow (MNF) method based on the inflow measurement at the MNF time. This model suffers from two major shortcomings. First one is use of estimated values for reported and unreported bursts and the second one is calculation of the total daily leakage by multiplying the leakage rate at the MNF time by 24. However, it is clear that arithmetic average cannot represent the total daily leakage, realistically. PRESMAC model (Mackenzie, 2001) is applied for pressure management purposes. As a disadvantage, this model does not use any hydraulic model and pressure is calculated with some simplifications which lead to high uncertainty especially in complex networks.

ECONOLEAK (Mackenzie and Lambert, 2002) calculates real losses using the annual water balance method in which, apparent losses are considered as a percentage of total NRW. Then using the BABE concept, the leakage components are evaluated. Therefore, it just uses estimated values to calculate the NRW components. Finally, BENCHLEAK model (Mackenzie et al., 2002) was written in an excel environment to calculate the NRW components using the water balance method.

To resolve the abovementioned weaknesses of the existing leakage models, this paper aims to develop comprehensive software to evaluate both apparent and real losses and their components. The model is able to be linked to hydraulic and GIS models to determine values of nodal and pipe leakage. The results can be represented in the GIS environmental to perform further analyses by decision makers.

Methodology

A computer program is developed to determine the non-revenue water and its components (apparent and real losses) using Visual Basic software. At first, the following information is extracted from a field study on all the properties for evaluation of the apparent losses components: Q_A (the mean monthly consumption of each connection), N_u (the number of unauthorized connections), N_O (the number of all active properties which the water company records show zero consumption for them), N_m (the number of connections which have not been illustrated in computer records of the water company), N_{FM3} (the number of connections which their meters show a low value of consumption less than a certain threshold), N_{AUB} (the number of authorized unbilled consumers). The related errors are identified as follows:

$$E_X = N_X \times Q_A \tag{1}$$

The following apparent losses components are resulted from Eq. (1): The unauthorized consumptions (E_u), the operational error (E_o), the management error (E_M) and the authorized unbilled consumption (C_{AUB}).

Also based on the filed investigation, the human errors (E_P) are determined from comparison of the meter readers' records and the amount of consumption from the billed records. Considering a statistical society, a percentage of meters, say 1-4% (Jeffcoate and Saravanapavan, 1989) is chosen and accuracy of the existing meters is tested. The start discharge rate of meters and the meter errors for the transient and maximum discharges are measured through the meter testing procedure. E_{FM1} is the un-metered consumptions and includes very small discharges (e.g. small and continues drops from stop taps and any leakage inside the properties) which cannot be measured by the meters. It is defined as follows:

$$E_{FM1} = [(0.1Q_S \times 24 \times 30 \times 12 \times N_A) + (5 \times 18 \times 12 \times 30 \times N_{LW1}) + (5 \times 8 \times 30 \times 3 \times N_{LW2})] / (12 \times 1000) \quad (2)$$

where N_A is the total connections, N_{LW1} is the total properties include internal tank, N_{LW2} is the number of properties with water cooling systems and Q_s is the start discharge rate of meter (lit/hr) identified by the meter testing.

E_{FM2} is the apparent losses caused by the meter errors in the range of transient to maximum discharge rates and is determined by,

$$E_{FM2} = ER_{FM2} \times N_A \times Q_A \quad (3)$$

in which ER_{FM2} is the average meter error in the range of transient to maximum discharges. Therefore, all the components of apparent losses are evaluated by summing of all the errors.

To calculate the components of real losses a field study should be carried out. It includes investigation of all the reported bursts that occur in the period of study, measurement of reservoir leakage and overflow, leakage from pumps and valves and network inflow and pressure rates. The flow measurement should be continued for a few days to be used by the MNF method. These data can be entered to the NRW model manually, or the output file of data loggers can be imported, directly.

The burst and accident data is entered to the program, or if special software is used in this regard, the related data can be imported from the output files of data loggers. The following relationships are applied to calculate the leakage rate from the reported bursts with different shapes of hole, crack and ring crack:

$$Q_{RB,h-c} = 5042.6 \times C_d \times A \times P^{0.5} \quad (4)$$

$$Q_{RB,rc} = 9505 \times a \times D \times P^{0.5} \quad (5)$$

where $Q_{RB,\,h\text{-}c}$ is the discharge from a hole or crack (lit/hr), C_d is a discharge coefficient (0.8 for a hole and 0.6 for a crack shape, (AWWA, 1992)), A is the leakage area (cm^2), P is the pressure (atm), $Q_{RB,\,rc}$ is the discharge from ring crack, a is the distance between two parts of the disconnected pipe and D is the pipe diameter.

Also the background leakage from mains and connections (Q_{BLM} and Q_{BLC}) are determined by the following equations:

$$Q_{BLM} = Q_{L,m} \times (P^{av} / 50)^N \times L_m \tag{6}$$

$$Q_{BLC} = Q_{L,c} \times (p^{av} / 50)^N \times n \tag{7}$$

in which $Q_{L,m}$ and $Q_{L,c}$ are the mean leakage rates from mains and connections that varies from 20-60 (lit/km/hr) and 1.5-4.5 (lit/conn./hr) for mains and connection pipes, respectively, for different infrastructure conditions of the network (UK/WI Report E, 1994). L_m and n are the pipe length and the number of connections, respectively and P^{av} is the network average pressure (m).

Having the network total background and burst leakage rates, the unreported burst can be determined using the annual balance method.

The other advantage of this methodology is calculation of performance indicators based on the IWA methodology (Farley and Trow, 2003). The procedure is as follows:

- Evaluation of the total real losses
- Calculation of the current annual real losses (CARL)
- Estimation of the unavoidable annual real losses (UARL)
- Calculation of the infrastructure leakage index ($ILI = \frac{CARL}{UARL}$)
- Choosing suitable economic safety factor (SF)
- Calculation of the economic annual real losses (EARL=UARL*SF)
- Comparison of the current and economic values of real losses
- Estimation of the feasible leak reduction (CARL-EARL)

Besides the annual water balance method, the software determines the daily and annual leakage rates using the minimum night flow (MNF) method and the FAVAD concept (Lambert 1997), as follows:

$$L = \sum_{t=1}^{24} L_t = L_{MNF} \times (P_t / P_{MNF})^N \tag{8}$$

where L and L_t are the daily and hourly leakage rates, respectively. L_{MNF} is the leakage flow at the MNF time. P_t and P_{MNF} are the network pressure at the times t and MNF, respectively. N is determined from the burst records based on the FAVAD method.

At the next step, the daily leakage flow is allocated to all nodes by a revolutionary procedure using the EPANET hydraulic model (Asadiani, 2004). Applying the emitter option in the EPANET and pressure dependent nature of leakage, the total daily leakage is distributed through all nodes. Then the pipes leakage rates are evaluated. The NRW computer program produces the required EPANET input files and then, the nodal and pipes leakage flows are calculated by the EPANET. At the final stage, the EPANET output results are directly imported to a GIS model and any required analysis together with the categorization of the NRW results can be performed in the GIS environment.

Case Study

To evaluate the introduced procedure and verify the software results, a case study was carried out in one of the Iranian cities with 5772 properties and 51.92 (km) pipe network. In this study four questioners were designed to gather all the related information about the properties, connections, meters and customers view points. During a field study, all the household and non-household properties inside the studied area were investigated and more than 40 items were identified. It should be mentioned that in countries like Iran, which all the domestic and small trade consumptions are metered, such information is very important to identify the apparent losses components. Figure 1 shows the apparent losses calculations for this network. It is seen that the main part of the apparent losses rate is because of the start discharge rate inaccuracy of the meters.

The reported bursts data was gathered for a period of 8 months via three questioners designed for this purpose with more than 30 items, which covers all available information during a burst repair activity. Some of these information are: time of awareness, arrival time, repair time, pipe data (e.g. type, diameter and depth), pressure, leakage area and shape, internal and external causes of the burst, pipe and soil conditions, all the information related to the personnel, components and equipments used for repair, etc. Figure 2 illustrates the reported burst calculations by the NRW software.

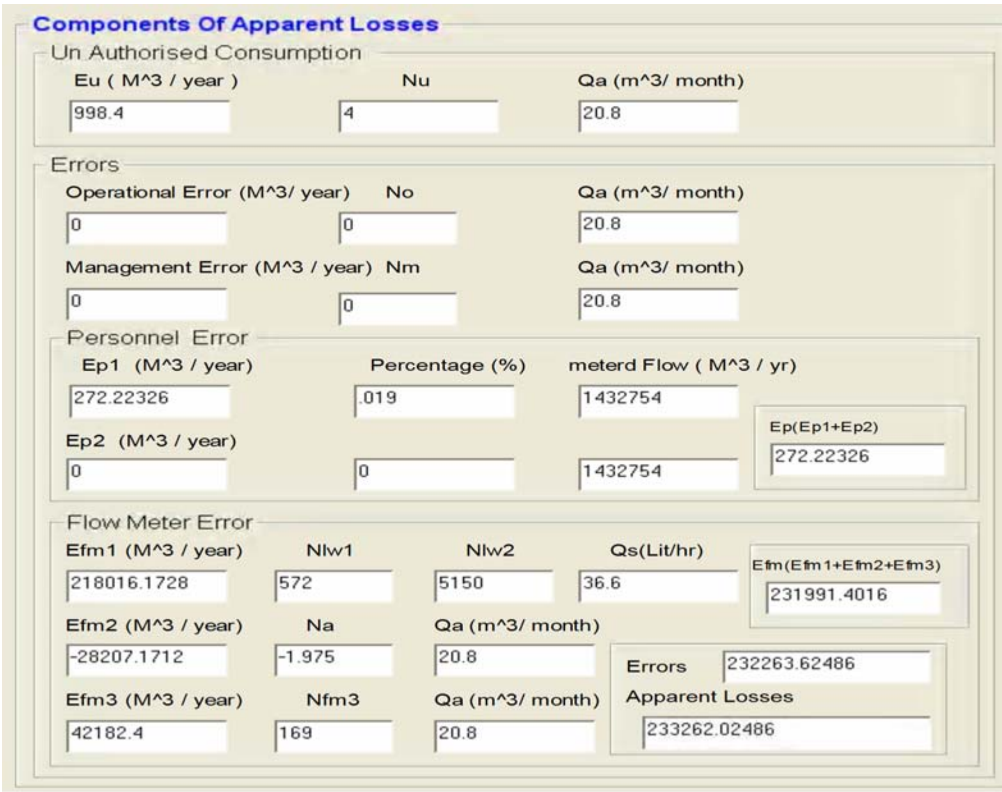
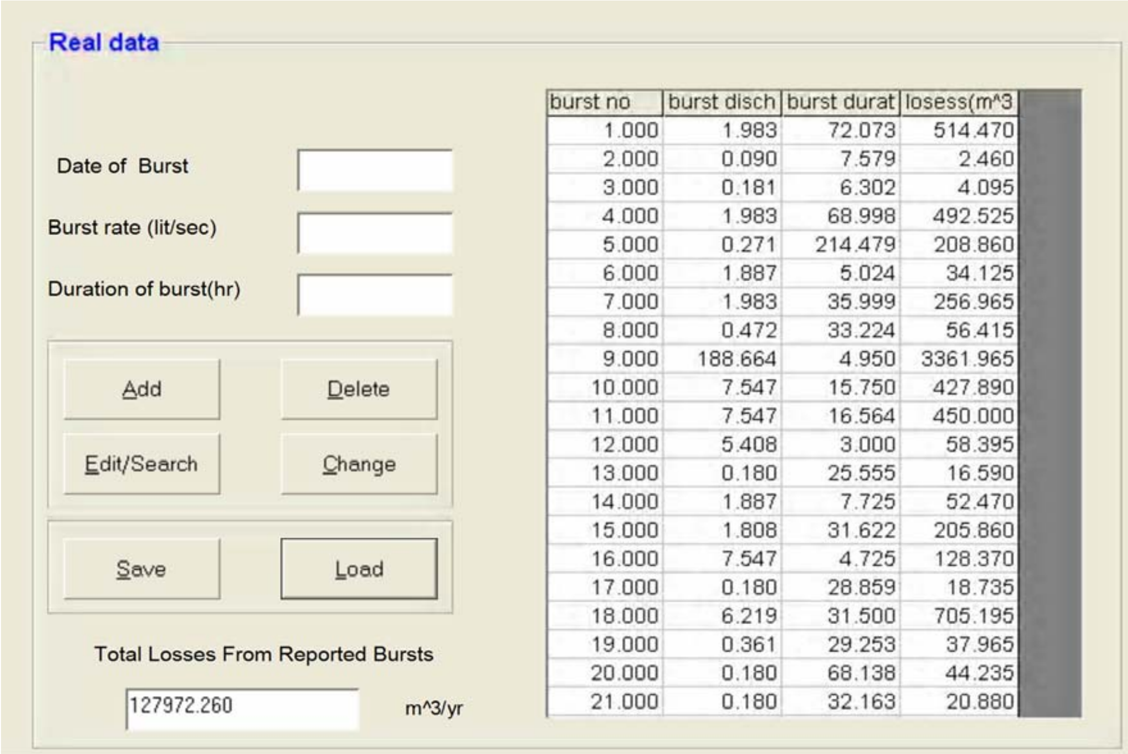


Figure 1 The apparent losses calculations



burst no	burst disch	burst durat	losess(m^3
1.000	1.983	72.073	514.470
2.000	0.090	7.579	2.460
3.000	0.181	6.302	4.095
4.000	1.983	68.998	492.525
5.000	0.271	214.479	208.860
6.000	1.887	5.024	34.125
7.000	1.983	35.999	256.965
8.000	0.472	33.224	56.415
9.000	188.664	4.950	3361.965
10.000	7.547	15.750	427.890
11.000	7.547	16.564	450.000
12.000	5.408	3.000	58.395
13.000	0.180	25.555	16.590
14.000	1.887	7.725	52.470
15.000	1.808	31.622	205.860
16.000	7.547	4.725	128.370
17.000	0.180	28.859	18.735
18.000	6.219	31.500	705.195
19.000	0.361	29.253	37.965
20.000	0.180	68.138	44.235
21.000	0.180	32.163	20.880

Figure 2 Leakage calculations for the reported bursts.

Figure 3 presents a summarization for the water losses components based on the annual water balance method, together with the performance indicators. All the apparent and real losses results are also presented in Table 1. It can be seen that the non-revenue water is about 41% of the total inflow. 75% of the NRW and 30.8% of the total inflow is wasted from the system as leakage. Total volumes of the un-reported bursts and leakage are 4.9 times of the water losses from the reported bursts. These results show lack of a proper scheme for active leakage control in this network.

The unavoidable leakage value is 113229 m^3/year and the economic annual real losses is 226458 m^3/year. It means that reduction of 522962 m^3/year of water losses is feasible. The ILI value (6.61) and the Economic Leakage Index (3.3) represent the poor infrastructure condition of this system. Economic efficiency of 30.21% illustrates that the decision makers just are able to control 30% of the total leakage in the existing situation and further reduction of 70% is accessible with more active leakage control schemes.

Leakage Performance Indicator

Water Supplied to System	2430245	M^3/yr
Authorised Consumption	1436868	M^3/yr
Non-revenue Water	996493	M^3/yr
Total Losses	993377	M^3/yr
Apparent Losses	243957.23	M^3/yr
Current Annual Real Losses (CARL)	749419.76	M^3/yr
Unavoidable Annual Real Losses(UARL)	113229.03	MCM/yr w.s.p
Unavoidable Annual Real Losses(UARL)	54.21	Lit/Connection/day w.s.p
Traditional Leakage Index	358.82	Lit/Connection/day w.s.p
Infrastructure Leakage Index (ILI)	6.61	
SF	2	
Economic Annual Real Losses	226458.07	M^3/yr w.s.p
Economic Annual Real Losses	108.42	Lit/Connection/day w.s.p
Economic Leakage Index	3.30	
Economic Efficiency	30.21	%
Volume of Non-revenue Water	41.00	as % of Annual System Input Volume
Value of Non-revenue Water		as % of Annual Cost of Runing the syestem
Reported Burst	127972.26	M^3/yr w.s.p
Background leakage	292843.23	M^3/yr w.s.p
UnReported Burst	328604.27	M^3/yr w.s.p

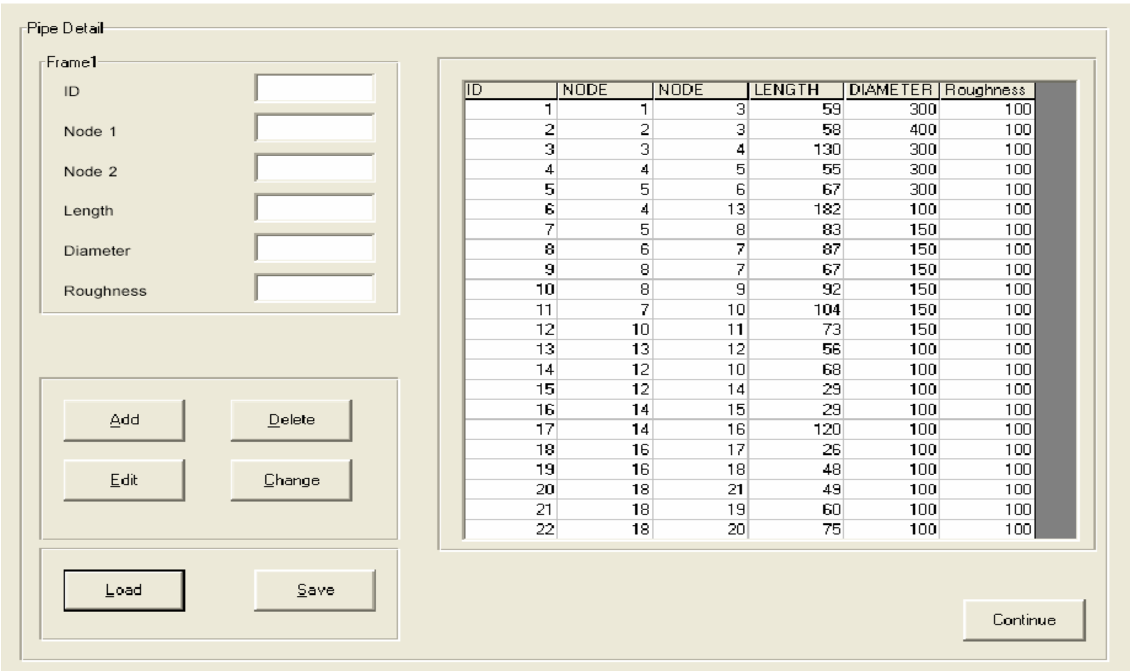
Figure 3 Water losses components and the performance indicators.

To determine the nodal and pipes leakage rates, the related EPANET input files are produced. As an example, Figure 4 shows the pipe data produced by the software.

After calculation of the new nodal and pipes hydraulic parameters and leakage by the hydraulic model, the output files are exported to the Arc/View. Figure 5 shows one of the queries which has been performed by the Arc/View. As a result, several scenarios can be selected and required output representations may be produced to support the decision makers for better management of the system.

Table 1 The components of apparent and real losses.

NRW Components	Percentage of inflow	Percentage of NRW	Lit/km/day	Lit /conn./day
Unbilled metered consumptions	0	0	0	0
Unbilled un-metered consumptions	0.13	31	164.4	1.5
Unauthorized consumptions	0.04	0.1	52.7	0.5
Errors	10	24.4	12820.5	115.3
Background leakage	12.1	29.4	15452.8	139
Reported bursts	5.3	12.8	6752.9	60.7
Un-reported bursts	13.5	33	17339.8	156



ID	NODE	NODE	LENGTH	DIAMETER	Roughness
1	1	3	59	300	100
2	2	3	58	400	100
3	3	4	130	300	100
4	4	5	55	300	100
5	5	6	67	300	100
6	4	13	182	100	100
7	5	8	83	150	100
8	6	7	87	150	100
9	8	7	67	150	100
10	8	9	92	150	100
11	7	10	104	150	100
12	10	11	73	150	100
13	13	12	56	100	100
14	12	10	68	100	100
15	12	14	29	100	100
16	14	15	29	100	100
17	14	16	120	100	100
18	16	17	26	100	100
19	16	18	48	100	100
20	18	21	49	100	100
21	18	19	60	100	100
22	18	20	75	100	100

Figure 4 The pipe data prepared by the software.

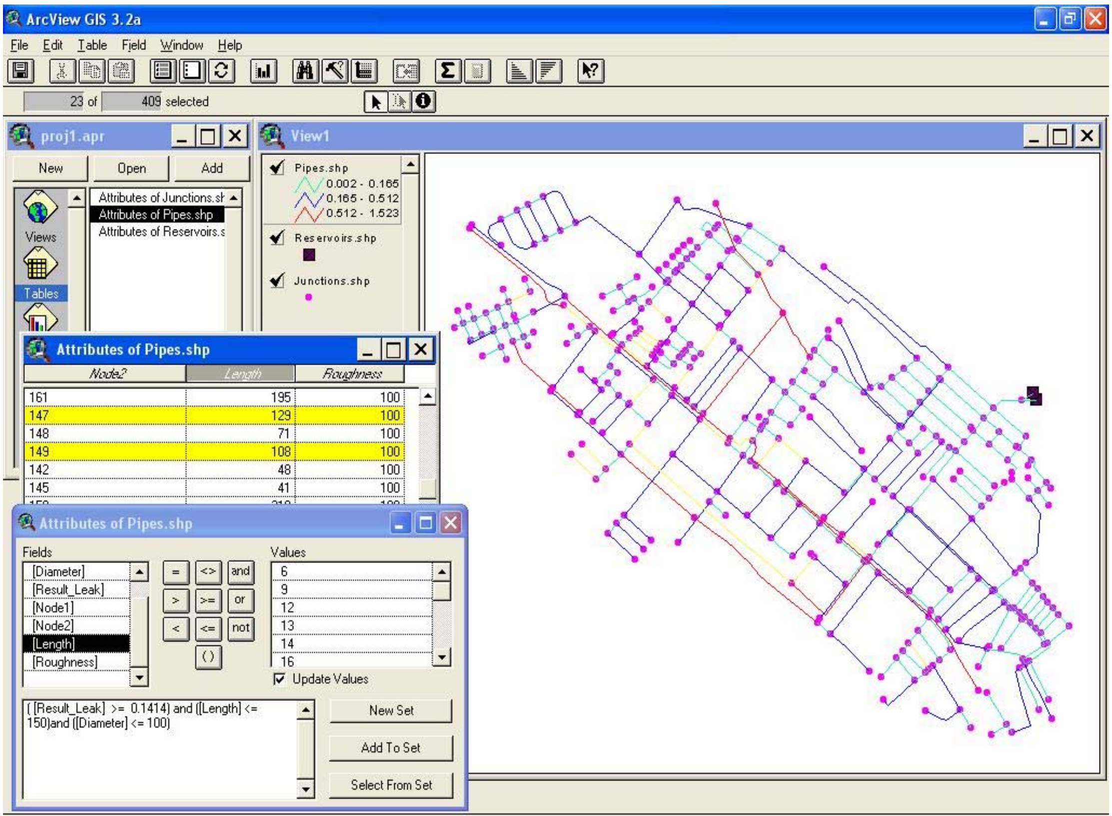


Figure 5 One of the analyses in the GIS environment (D < 100 mm, L < 150 m and Leakage > 0.14 lit/s).

After determining the NRW components, some active NRW control schemes should be designed and performed to reduce the total amounts of the apparent and real losses to the optimum economical level. Table 2 illustrates cost of the proposed apparent losses reduction scenario. Figure 6 shows that the optimum economical level for reduction of apparent losses is 170000 m^3/year. It can be concluded that just reduction of 30% of apparent losses is economical in this network.

Table 2 the cost of apparent losses reduction.

Step	Procedure	No.	Cost (MRial)*		
			Unit	Total	
1	Removing unauthorized connections	4	0.28326	1.13	2.26
	Meter installation	4	0.28326	1.13	
2	Change of faulty meters	169	0.16686	28.2	123.64
	Change of 10% of the non-accurate meters (per year)	572	0.16686	95.44	
3	Change of 20% of the meters after expiration of their real life	1142	0.16686	190.89	190.89

*9000 Rial = 1 US$

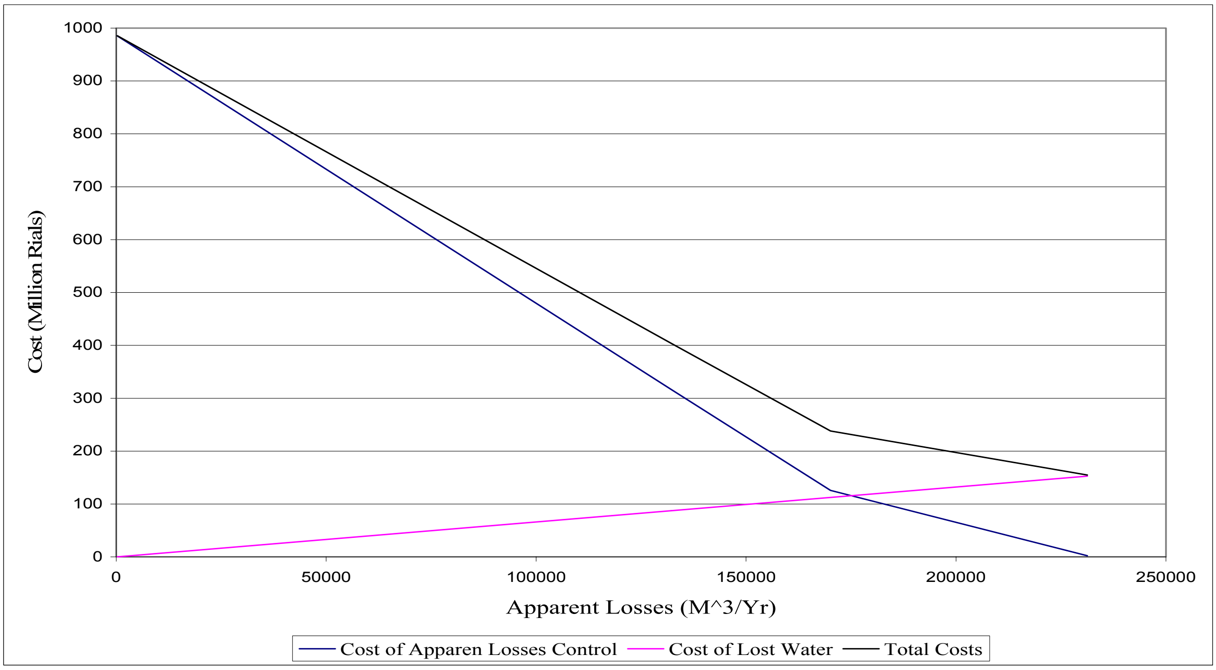


Figure 6 Apparent losses reduction vs. cost.

Furthermore, the same analysis was carried out to obtain the optimum level of real losses reduction in the studied area in year 2003. The real losses cost includes cost of the following items: flow and pressure measurements, leak detection and location schemes, repair of the reported and un-reported bursts and replacement of 10% of pipes during each year. According to the cost-benefit analysis the leakage target level is 226458 m3/year.

Summary and Conclusions

In this paper a computer program is produced to evaluate the non-revenue water in water distribution systems. This software determines all the components of apparent losses which are so important in developing countries, together with the real losses components and infrastructure leakage indicators. In conjunction with a hydraulic model, values of nodal and pipes leakage are obtained, considering the pressure dependency of leakage. Then using a GIS software, an appropriate environment is prepared for better representation of the results and to help the decision makers.

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