Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2015.1049967

57 (2016) 11436–11446
May

Taylor & Francis
Taylor & Francis Group

Non-revenue water reduction through pressure management in Kozani's water distribution network: from theory to practice

V. Kanakoudis*, K. Gonelas

Department of Civil Engineering, University of Thessaly, 38334 Volos, Greece, Tel. +30 24210 74156; Fax: +30 24210 74135; emails: bkanakoud@civ.uth.gr (V. Kanakoudis), gonelas@uth.gr (K. Gonelas)

Received 14 February 2015; Accepted 6 May 2015

ABSTRACT

During the last few years, many water utilities are facing difficulties with the high non-revenue water (NRW) levels. Among the NRW management strategies, water pressure management (PM) is the most popular towards the goals of effective and efficient water use. In an effort to improve the level of services provided to consumers, minimize its operating expenses and reduce water leakage and pipes' bursts, water utilities rely on water PM although it is one of the most expensive methods. This study analyses a methodology of calculating economic benefits and revenue losses caused due to the reduction of a system's operating pressure. The reduction of System Input Volume causes direct benefits (e.g. reduced energy costs), while the reduced burst frequency causes direct (e.g. maintenance cost reduction) and indirect potential benefits (e.g. reduction in personnel, insurance and vehicle operation costs). The revenue losses are caused mainly due to the reduction of pressure-dependent water consumption. In the case of Kozani city in Greece, the economic impact of dividing its water network in District Metered Areas and applying 5 PM interventions based on installing Pressure Reducing Valves is calculated, using the system's hydraulic model.

Keywords: District Metered Areas; Pressure management; Water savings; Non-revenue water

1. Introduction

During the last decades, a number of water utilities began to practice and promote active pressure management (PM) as they realized that, by reducing excess pressure, the number of leaks and bursts occurring in their water distribution systems (WDSs) could be significantly reduced. Combining PM with District Metered Areas (DMAs) configuration, a strong leakage management tool can be created [1–5]. It is widely acknowledged by the water utility managers worldwide that PM leads to reduced leak flow rates and bursts repair costs both for pipe mains and service connections as well [4–7]. Yet, the anxiety of losing revenues related to reduced water pressure provided to the customers' water metres or the difficulty to predict the benefits which might justify the needed investment costs, prevented water utilities from PM projects implementation. In systems with continuous

*Corresponding author.

Presented at the 12th International Conference on Protection and Restoration of the Environment (PRE XII)
29 June–3 July 2014, Skiathos Island, Greece

supply, rapid reductions in bursts and repair costs are now changing the cost-effectiveness view of PM and the perception that leaks and bursts can only be managed by repairs or pipe replacement. Utilities that have recently implemented PM projects are now realizing that there are more benefits than reduced leak flow rates and burst repair costs, such as efficient demand management, water conservation and asset management. There have been efforts during recent years [8–10] in order to emerge pressure and leakage management as one of the policies which will achieve water balance and delay expansion of infrastructure. Efforts have been made also to identify the positive effect of reducing the operating pressure of water networks and mainly the reduction of pipe breaks [11].

The appropriate path to apply a PM project starts by dividing the entire network in smaller "hydraulically isolated" regions (DMAs) as it is easier to manage and inspect them compared to the entire WDS. A pressure control device is installed usually in the entering point ("head") of each DMA to ultimately reduce the non-revenue water (NRW) in this area. Pressure affects differently each of the three main NRW components (unbilled authorized consumption, apparent losses and real losses). Only some parts of unbilled authorized consumption (irrigation of municipal gardens, cleaning of mains/sewers, etc.) are influenced by pressure reduction. Regarding apparent losses, unauthorized consumption (theft or illegal use) vary similarly to pressure; water metering errors (readings errors or data handling) remain unchanged while water metres' inaccuracies increase to a small extent in relation to pressure reduction. Real losses (largest NRW component) represent water volumes lost due to all types of leaks, breaks and overflows of the mains, tanks and customers' connections and service pipes, up to the point of the water metre, and follow the change in pressure.

The required optimization of both the network's division into DMAs and PRVs location and can be achieved by testing scenarios developed through the network's calibrated and validated hydraulic simulation model. Recently, several methods have been proposed for optimized network partition [12–15] and for PM implementation combined with hydraulic modelling [7,16]. In the case of Kozani's (a city in north-western Greece) WDS, 24 DMAs were formed and a lot of PRVs were simulated in its model. Pressure reduction within acceptable limits resulted in reduced System Input Volume (SIV), since the actual water use and water losses are both reduced, as being pressure dependent. The pressure-dependent demand (PDD) function of the Bentley WaterGEMS software contributed to this "dependence" simulation. The impacts of five different PM scenarios including installation of a number of PRVs in some of the already formed DMAs were estimated and compared to the base scenario that included only the initial formation of the DMAs. Then, a prioritization of these five PM scenarios took place, based on the network's hydraulic operation.

The net present value (NPV) of each PM scenario's results was calculated for a 15-year period considering both the economic benefits and revenue losses arising from the network's pressure reduction. Among the economic benefits that should be assessed, were the annual reduction of the net energy cost due to the reduction of the SIV and the decrease of the annual costs related to the reduced pipe bursts frequency. The latter leads to reduced maintenance, personnel, insurance and vehicles operation costs. For a more precise analysis, the economic benefits were distinguished to direct (e.g. reduction of energy and maintenance costs) and indirect (e.g. reduction of personnel, insurance and vehicles operation costs). The expenses related to each PM scenario include installation, maintenance and replacement costs, and especially, the revenue losses due to the reduced (pressure dependent) water being sold. A detailed cost-benefit analysis proved the cost-effectiveness of each PM scenario.

2. The economic impact of PM

2.1. Economic benefits

An important benefit results from SIV reduction and the reduction of energy costs related. The volume of water savings changes in time according to the total SIV variation. The economic benefit S_1 for each year n after the PM implementation, can be calculated using Eq. (1), while energy cost $C_{\text{marg(E)}}$ and treatment cost $C_{\text{marg(T)}}$ are calculated using Eqs. (2a) and (2b), respectively.

$$S_{1(n)} = \left[R_{\text{SIV}} \times (1 + r_{\text{SIV}})^n \times 365 \times (C_{\text{marg(E)}} + C_{\text{marg(T)}})\right] \times (1 + r_n)^n \tag{1}$$

$$C_{\text{marg(E)}} = \text{OM}_2^*/Q_{\text{SIV}} \tag{2a}$$

$$C_{\text{marg(T)}} = \text{OM}_5^*/Q_{\text{SIV}} \tag{2b}$$

where $S_{1(n)}$ (€) is the annual economic benefit in year n; R_{SIV} (m^3/day) is the SIV reduction of all DMAs; r_{SIV} (%) is the annual SIV variation; $C_{\text{marg(E)}}$ (€/m^3) is the energy cost of all processes (except for administration) of urban water supply; $C_{\text{marg(T)}}$ (€/m^3) is the water treatment cost; r_n (%) is the annual inflation rate; n represents the years from the year of PM scenario application; OM_2^* (€) is the annual energy cost of all processes (excluding administration); OM_5^* (€) is the annual consumables cost of water treatment process (including chlorine, chemicals etc.); Q_{SIV} is the annual SIV (m^3).

Pressure reduction leads to reduced real loss related to background leakage, reported and unreported leaks. The burst frequency is also reduced, since the infrastructure operates more within its resistance limits. The reduction rate of bursts frequency refers to a zone or a DMA area and depends on the pipe material, the maximum operating pressure and the rate of new breaks that are non-pressure dependent according to Eq. (3) [17]. The reduction in burst frequency can be also identified through Fig. 1. The average zone point (AZP) is the node with the average operating pressure of a DMA, is found with the help of the hydraulic model and is verified through field measurements.

$$\text{BF}_\text{R} = \left(1 - \frac{\text{BFnpd}}{\text{BF}_0}\right) \times \left(1 - \left(\frac{P_1}{P_0}\right)^3\right) \tag{3}$$

where BF_R (%) is the reduction in bursts frequency of a DMA; BF_{npd} is the non-pressure-dependent burst frequency per 100 km/year; BF_0 is the burst frequency before PM per 100 km/year; P_1 (kPa) is the maximum operating pressure at the AZP after PM; and P_0 (kPa) is the maximum operating pressure at the AZP before PM.

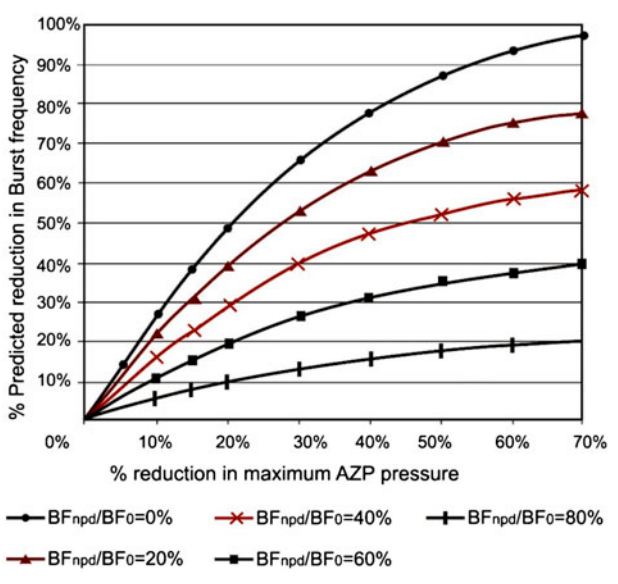

Fig. 1. Reduction (%) in burst frequency vs. reduction (%) in AZP pressure [17].

Reducing the rate of new breaks results in both direct economic benefits, such as maintenance cost reduction and also indirect potential benefits, such as personnel, insurance and vehicles operation costs reduction. The former are calculated for all PM scenarios and for each DMAi separately. This is because the factors of Eq. (3) are determined to a DMA level, while the economic benefit S_1 is calculated with respect to the entire network. The annual economic benefit S_{2i} of each PM scenario for each DMAi can be calculated by considering also the number of connections and the pipes' total length of each DMAi according to Eq. (4). The annual benefit for the entire network is the sum of all annual benefits per DMA according to Eq. (5). In addition to the direct benefit, on a long-term perspective, also other costs are reduced due to the reduction in burst and leaks frequency. The annual benefit $S_{3i(n)}$ of each PM scenario for each DMAi and for the entire network is calculated according to Eqs. (6) and (7), respectively. The direct annual benefit equals to the sum of $S_{1(n)}$ and $S_{2(n)}$, while $S_{3(n)}$ is added in order to determine the total (direct and indirect) annual benefit.

$$S_{2i(n)} = [(a_\text{c} \times a_{\text{N}ci}) + (a_\text{m} \times a_{\text{L}mi})] \times \text{BF}_{\text{R}i} \times a_{\text{OM}_4} \times \text{OM}_4^* \tag{4}$$

$$S_{2(n)} = \sum_1^i S_{2i(n)} \times (1 + r_n)^n \tag{5}$$

$$S_{3i(n)} = [(a_\text{c} \times a_{\text{N}ci}) + (a_\text{m} \times a_{\text{L}mi})] \times \text{BF}_{\text{Ri}} \times (\alpha_{\text{LR15}} \times \text{OM}_{15} + \alpha_{\text{LR65}} \times \text{OM}_{65} + \alpha_{\text{LR85}} \times \text{OM}_{85}) \tag{6}$$

$$S_{3(n)} = \sum_1^i S_{3i(n)} * (1 + r_n)^n \tag{7}$$

where a_c is the % of connection pipes breaks to the total breaks occurring; $a_{\text{N}ci}$ is the % of connections in DMAi to the total number of connections; a_m is the % of distribution pipes breaks to the total breaks occurring; $a_{\text{L}mi}$ is the % of pipes length of DMAi to the total pipe length of the network OM_4^* (€) is the maintenance cost of all procedures apart from the administration; a_{OM_4} is a factor that determines the % of maintenance costs OM_4^* spent on bursts restorations; OM_{15}, OM_{65} and OM_{85} represent the personnel, insurance and vehicle operation costs of water distribution process, respectively; α_{LR15}, α_{LR65} and α_{LR85} are cost impact factors, due to leaks and breaks in mains and service connections, of personnel, insurance and vehicle operation costs, respectively; BF_{Ri} (%) is the reduction in bursts frequency of DMAi.

2.2. Expenditures and revenue losses

Economic outflows are the equipment purchase and installation costs occurring at the beginning of the investment (i.e. each PM scenario) and their replacement costs after the end of their lifetime (usually after a decade). The purchase and installation costs of all valves, flanges, bypass pipes and other fitments needed for the proper installation of each PRV are considered. To calculate the total cost investment of each PM scenario, the purchase and installation cost of any equipment were placed in year 0 (present time), while its replacement cost in year n (end of its lifetime) according to Eq. (8). Management and maintenance costs (O_2), which mostly reflect the personnel cost for carrying out the management, have to be allocated along time according to Eq. (9).

$$O_{1(n)} = I_1 \times (1 + r_n)^n \tag{8}$$

$$O_{2(n)} = I_2 \times (1 + r_n)^n \tag{9}$$

where $O_{1(n)}$ (€) are the annual expenses for purchase, installation and replacement of the equipment; $O_{2(n)}$ (€) are the annual management and maintenance costs; I_1 and I_2 (€) are the initial capital for O_1 and O_2, respectively, at year 0.

Regarding the revenue losses due to the system's reduced pressure, the (pressure-dependent) water volume not consumed varies in time according to the system's pressure and consequently to the SIV variation. The lost revenues (O_3) in each year n resulting from each PM scenario implemented can be calculated using Eq. (10). The costs of studies (O_4) are placed at the beginning of the investment and are considered as expenditures. $\sum_{k=1}^{4} O_{k(n)}$ represents the total annual expenditures.

$$O_{3(n)} = \left[a_{PDD} \times \left(\frac{Q_{RW}}{Q_{SIV}}\right) \times R_{SIV} \times (1 + r_{SIV})^n \times 365 \times p_{marg}\right] \times (1 + r_n)^n \tag{10}$$

where $O_{3(n)}$ (€) are the annual revenue losses; a_{PDD} is the % of the billed water demand which is pressure dependent; Q_{RW} (m^3) is the annual volume of revenue water; Q_{SIV} (m^3) is the annual SIV; and p_{marg} (€/m^3 is the marginal water price.

The annual NPV for each year n due to the implementation of PM can be calculated using Eq. (11).

$$NPV_{(n)} = \frac{\left[\sum_{k=1}^{3} S_{k(n)} + \sum_{k=1}^{4} O_{k(n)}\right]}{(1 + r_n)^n} \tag{11}$$

3. Implementation

3.1. Basic characteristics of Kozani's WDS and its hydraulic model

Kozani city, capital of Kozani County in West Macedonia Region, is located in the northern part of Aliakmonas river valley. The city lies 710 m above sea level, 15 km north-west of the artificial lake Polyfytos, 120 km south-west of Thessaloniki, between Pieria, Vermio, Vourinos and Askio mountains. The population of Kozani municipality exceeds 70,000 people. The customers served by the local water and sewage utility (called DEYAK) are almost 50,000 people. Its widely spread well-designed WDS covers a huge area (Fig. 2), including the entire city and its expansions in more than ten suburbs. The total daily water volume supplied by the WDS reaches its peak (22,744 m^3) during July, while dropping to just 18,584 m^3 on January. Vathylakkos boreholes (to the south) supply Kozani during summer, while Ermakia springs (to the north) during winter. There are three pressure zones formed: (a) a limited higher zone to the north (altitude ranging from +750 to +800); (b) a middle zone (altitude ranging from +710 to +750); and (c) a low zone to the south (altitude ranging from +610 to +710), covering 60% of the total water demand (Fig. 2). There are two main water storage tanks and also a tank system

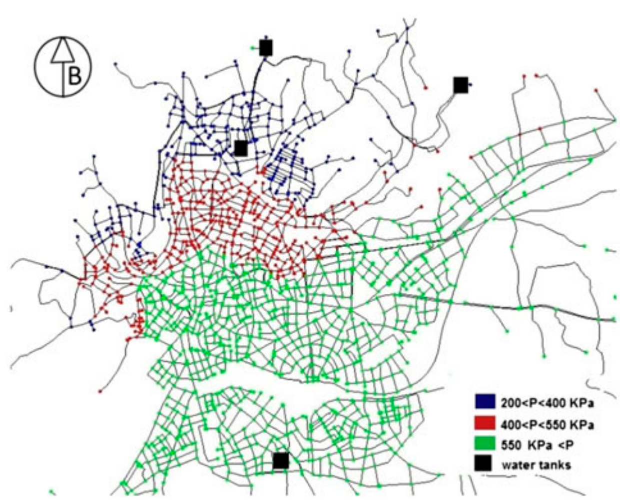

Fig. 2. Kozani city WDS pressure zones and water tanks.

which supplies only the middle zone. The hydraulic model of Kozani's WDS consists of 211.86 km pipes and water mains, 1,817 nodes and 8 tanks (the 3 mentioned above and 5 minor tanks supplying the suburbs). DEYAK has applied a GIS system setting coordinates to all its 28,500 water metres. The residential demand spatial allocation was based on the spatial information of each hydrometer. Water losses were introduced into the model as individual consumption with its own temporal and spatial allocation. The former was based on residential demand allocation, which was modified by spatial coefficients representing pipes' age and material and operating pressures at a DMA level. After the model was developed, its calibration and verification followed. The modelling software used was Bentley's WaterGEMS. Pressure and flow was recorded (every 3 h) in specific points of the network, using data from SCADA. Pressure data from additional nodes were recorded using an accurate portable pressure metre. The software's Darwin Calibrator module was used for the pipes roughness adjustment.

3.2. Forming the DMAs in Kozani's WDS

There are certain rules to obey forming DMAs. Both the fire flow requirements and the network's nodal pressures developed should be considered right from the start of the process. All possible alternative DMAs formations must have these two basic principles in common. As Kozani's WDS is widely spread, it was separated into 24 DMAs [18] so that none of those exceeds the limit of 2,000 customers' water metres being served. The network was divided in DMAs using the hydraulic model by trial and error method. When designing the DMAs, other sub-rules considered had to do with water mains length, population density and various specificities of the terrain (e.g. roads, parks). The hydraulic efficiency of the proposed DMAs was also considered to avoid causing problems at each DMA's critical nodes (where the lowest operating pressure values appear), when closing the isolation valves installed at the DMA's borders to ensure its hydraulic isolation. A water flow re-establishment inside the WDS' pipes following DMAs' formation, led to a DMAs' input water volume variation, ranging from −7.3% (DMA 8) to +6.76% (DMA 11K) (Fig. 3). Concerning the total network, a 2.22% reduction (144,594 m^3/year) of the SIV was noted.

Since Kozani's WDS is not radial and there are mains crossing the city from edge to edge, several DMAs formed in series (obeying to the abovementioned rules) are supplied by the same water main. Thus, any PRV's activation in the central DMAs affects other downstream DMAs supplied by the same water main. Based on that fact, five PM scenarios below were configured. The particular morphology of the network combined with the interventions' performance (in water savings) dictated the successiveness of the interventions. To ensure their performance, it is necessary to implement them with the proposed order. The application of the nth intervention implies the implementation of the $(n-1)$th intervention. Table 1 presents SIV reduction caused by the DMAs formation and each one of the 5 PM interventions.

(1) PM intervention No. 1: Installation of a PRV in each one of the 4 "big or inner" DMAs (i.e. A, B, C, D) that cover the largest part of the network (4 PRVs installed in total) (Fig. 4(a)).
(2) PM intervention No. 2: Installation of PRVs in DMA B. Initially, DMA B is divided in 5 sub-DMAs (i.e. M, 5, 4A, 4K, K-1), and then, a PRV is installed in each one of the sub-DMAs 5, 4K and K-1 (3 PRVs installed in total) (Fig. 4(b)).
(3) PM intervention No. 3: Installation of PRVs in DMAs C and A. Initially, DMA C is divided in 3 sub-DMAs (i.e. 12, 6, 7) while DMA A in 4 sub-DMAs (i.e. 11A, 11K, 10, 14K). Then, a PRV is installed in each one of the sub-DMAs 6, 7, 10, 14K (4 PRVs installed in total) (Fig. 4(c)).

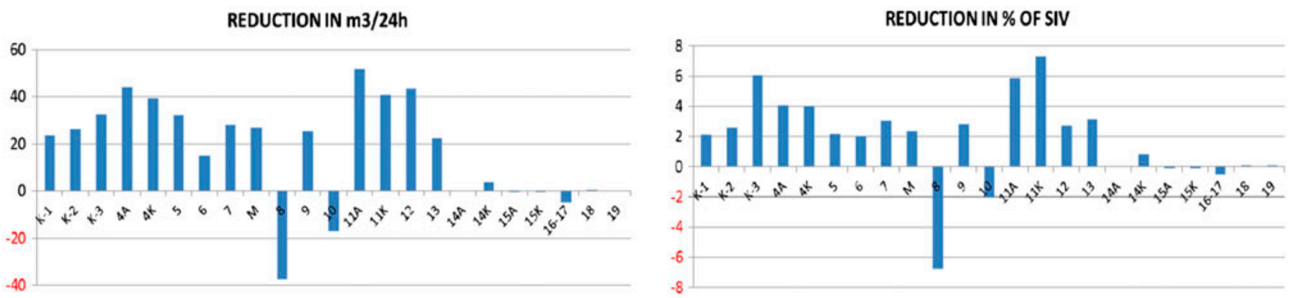

Fig. 3. Reduction in m^3/d and % SIV during a typical day of August 2011 for each DMA.

Table 1
Water savings after applying the PM scenarios in Kozani's WDS (SIV base year: 2011)

PM interventions	Water savings (m^3/year)	% SIV	PM interventions	Water savings (m^3/year)	% SIV
DMAs formation	298,935	4.32	3rd intervention	156,585	2.26
1st intervention	1,316,190	19.02	4th intervention	198,560	2.87
2nd intervention	231,775	3.35	5th intervention	102,200	1.48
			Total	2,304,245	33.29

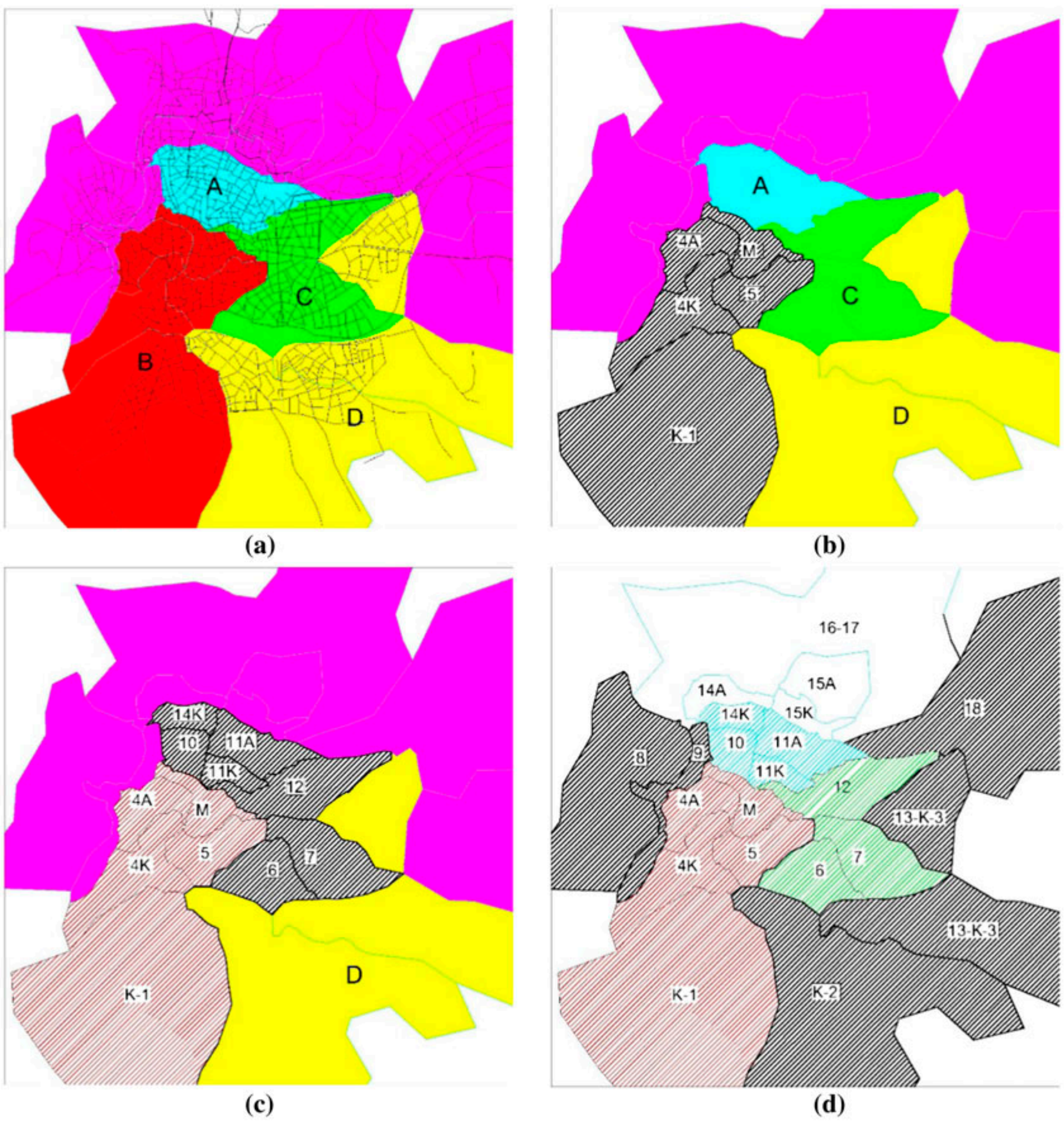

Fig. 4. PM interventions No 1–4 tested for Kozani's WDS including PRV installation: (a) 4 PRVs in the 4 big inner DMAs (A, B, C, D); (b) 3 PRVs in the inner DMA B divided in 5 sub-DMAs; (c) 4 PRVs in the inner DMAs C and A divided in 3 and 4 sub-DMAs, respectively; and (d) 5 PRVs in the inner DMAs B, D and outer DMAs 8, 9 and 18.

(4) PM intervention No. 4: Installation of PRVs in the inner DMAs B, D and the outer ones 8, 9 and 18. Initially, DMA D is divided in 3 sub-DMAs (i.e. K-2, 13-K-3). Then, a PRV is installed in each one of the sub-DMAs K-2, 4A and the outer DMAs 8, 9, 18 (5 PRVs installed in total) (Fig. 4(d)).

(5) PM intervention No. 5: Installation of PRVs in the sub-DMAs M, K1, 4A, 4K, K-2, and the outer DMAs 8, 9, 10 and 12: (12 PRVs installed in total).

3.3. The economic benefits of DEYAK WDS's PM

The profits from the PM interventions applied were calculated in a 15-year period in terms of NPV. In order to calculate the annual savings due to SIV reduction, an annual SIV increase r_{SIV} equal to 3% was considered, consistent with the SIV variation in DEYAK over the last 10 years [18]. The annual inflation rate r_i was considered equal to 3%. The energy cost $C_{\mathrm{marg(E)}}$ and other data related to the full water cost were calculated in a previous research work of the authors [19]. The SIV for 2011 was 6,921,387 m^3 and $C_{\mathrm{marg(E)}}$ was equal to 0.129 €/m^3. The factors α_{LR15}, α_{LR65} and α_{LR85} were equal to 0.8. Since the burst frequency reduction differs for each DMAi, the economic benefit was calculated for each of the five PM interventions, following the definition of the pressure reduction caused by each PM intervention in each DMAi separately. Pilot PM implementation took place in sub-DMAs 6 and K-1, in order to estimate the $\mathrm{BF_{npd}/BF_0}$ term depending on the maximum pressures at average zonal pressure (AZP) nodes listed in Table 2. AZP maximum operating pressures P_0 and P_1 before and after each successive intervention, respectively, were assessed through the hydraulic model as the averages of the maximum operating pressures of all nodes in each DMAi.

The direct economic benefits due to reduction of maintenance costs were calculated first. The maintenance cost of all procedures (administration excluded) OM_4^* for 2011 was 232,128.08 €, a_{OM_4} was considered equal to 0.57 (since the maintenance and replacement costs within the distribution network equal to 132,238.52 €). The factors a_c, $a_{\mathrm{N}ci}$, a_{m} and $a_{\mathrm{L}mi}$ are known because the number of service connections in each DMA and the pipes total length of each DMA are known. Table 3 presents the annual economic benefits after each PM intervention. Then, the calculation of indirect benefits due to reduction in personnel, insurance and vehicle operation costs followed. The OM_{15}, OM_{65} and OM_{85} which represent the personnel, insurance and vehicle operation costs of water distribution process, respectively, were equal to 1,023,324.35 €, 256,340.37 € and 33,297.64 €.

Table 2
Estimation of the term $\mathrm{BF_{npd}/BF_0}$ for DEYAK WDS

$\mathrm{BF_{npd}/BF_0}$	$P_{\mathrm{AZPmax(0)}}$ (kPa)
0.8	$200 < P_{\mathrm{AZPmax(0)}} < 400$
0.6	$400 < P_{\mathrm{AZPmax(0)}} < 600$
0.4	$600 < P_{\mathrm{AZPmax(0)}} < 800$
0.2	$800 < P_{\mathrm{AZPmax(0)}} < 1{,}000$
0.05	$1{,}000 < P_{\mathrm{AZPmax(0)}} < 1{,}500$

3.4. The expenditures of DEYAK WDS's PM

The cost of purchase and install valves, flanges and other fitments required to connect a PRV were taken into account, along with the corresponding costs of PRVs, electromagnetic flow metres and telemetric

Table 3
The annual benefits for the year 0 due to reduction in SIV and in burst frequency

	Profit (€) in year 1		
		Due to reduction in burst frequency	
Interventions	Due to SIV reduction	Maintenance cost reduction	Personnel, insurance and vehicle operation cost reduction
Initial status	–	–	–
DMAs formation	41,688	1,106	8,785
1st intervention	183,624	22,007	174,807
2nd intervention	32,312	6,516	51,760
3rd intervention	21,830	3,697	29,366
4th intervention	27,716	10,625	84,395
5th intervention	14,263	2,306	18,313
Total	321,433	46,257	367,426

recorders. Finally, the cost to construct the underground chambers, in which the PRVs will be installed, was assessed. Ten years after the installation, part of the equipment (mainly the PRVs) should be renewed due to their continuous use related ageing, at a cost equal to half of the initial implementation cost. On the contrary, bypass pipes, valves and the underground chambers will not need to be replaced at the same time in the future. Management cost of equipment was mainly personnel costs related to the implementation of the PM interventions. Maintenance of fitments, retail equipment and valve changes were considered to be maintenance costs. Calculating each PM intervention's NPV, maintenance and management costs are considered to be included in the existing cost of DEYAK. Table 4 shows the four components of the annual expenditures for the years 0 and 1. In the base year 0 (PRVs' installation), only installation costs (O_1) and study expenses (O_4) occur, while in year 1, revenue loss due to pressure-dependent water demand not supplied (O_3) take place. There are no management and equipment maintenance costs (O_2) regarding the PM interventions application for DEYAK. Following the calculation of the annual SIV reduction for each one of the five PM interventions (plus the initial one including only the formation of the DMAs), the revenue losses due to the reduced water volume supplied and thus billed was calculated. Table 5 presents the SIV, the billed metered consumption, the unbilled unmetered consumption, the apparent and the real losses for 2011, and also, which part of these water volumes is pressure dependent. As the analysis showed that 36.92% of the SIV generates revenues, while 60% of it is pressure-dependent [19], the water volume that will eventually lead to revenue losses due to PM is 22.15% of the SIV.

4. Results and discussion

PM through forming DMAs and installing the necessary PRVs results in important outputs. The network was resolved for the 12 months of the base year (2011). Afterwards, the annual economic benefits and expenditures were calculated for a 15-year period following 2011, with average annual inflation equal to 3% and an average annual SIV increase also equal to 3%. The reduction of burst frequency due to a reduction of the maximum network operating pressures led to reduced pipe breaks and therefore to direct maintenance cost reduction. Fewer broken pipes imply less staff needed for repairs, which means a reduction in personnel, insurance and vehicle operation costs. While the implementation of the latter depends on the will of water utilities for redundancies, the benefits will occur even with the non-replacement of the staff close to retirement. It has been necessary therefore to

Table 4
The annual expenditures for the years 0 and 1 due to PM implementation

	Expenditures (€) in year 0				Expenditures (€) in year 1			
Interventions	O_1	O_2	O_3	O_4	O_1	O_2	O_3	O_4
Initial status	–	–	–	100,000	–	–	–	–
DMAs formation	10,000	–	–	–	–	–	32,081	–
1st intervention	150,240	–	–	–	–	–	141,309	–
2nd intervention	107,427	–	–	–	–	–	24,866	–
3rd intervention	136,408	–	–	–	–	–	16,800	–
4th intervention	179,674	–	–	–	–	–	21,329	–
5th intervention	168,573	–	–	–	–	–	10,976	–
Total	752,322	–	–	100,000	–	–	247,361	–

Table 5
Components of SIV and their rates of pressure dependency

	Water volume (m^3)	% of pressure dependent	Generates revenue?
Billed metered consumption	2,555,471	60	Yes
Unbilled authorized consumption	138,428	100	No
Apparent losses	761,353	60	No
Real losses	3,466,135	100	No
SIV (for the entire network)	6,921,387	–	–

calculate the NPV of interventions considering either only the direct benefits or both these benefits along with the indirect potential benefits.

In the case where only the direct benefits are considered (Fig. 5), the NPV of the "forming DMA's" intervention gets positive from the very first year, PM intervention 1 from the 4th after, PM intervention 2 from the 8th year after and PM intervention 4 from the 14th year after. In case of all interventions' implementation, the break-even will occur between the 8th and the 9th year. After the end of the 15-year period, the "forming DMA's" intervention will bring in 173.684 € as NPV, 760,742 € for PM intervention 1; 81,117 € for PM intervention 2 and 25,953 € for PM intervention 4. All together bring in 1,041,495 €. According to this intervention, 12 PRVs are required to be installed in total. In contrast, PM interventions 3 and 5 both generate losses equal to 41,657 and 300,956 €, respectively. Fig. 5 demonstrates the gradual evolution of the NPV for each PM intervention separately and for all of them applied at the same time.

In the case where the overall potential benefits are considered, the cost-effectiveness of each PM intervention is greatly increased. The NPVs of the "forming DMA's" intervention and PM intervention 1 get positive from the very first year, PM interventions 2 and 4 from the 2nd year after, PM intervention 4 from the 4th year after and PM intervention 5 from the 10th year after. If all interventions are implemented at the same time (base year 0), the overall NPV gets positive after the 2nd year. After the end of the 15-year period, the "forming DMA's" intervention will bring in 305,462 € as NPV, 3,432,800 € for PM intervention 1; 857.523 € for PM intervention 2; 398,826 € for PM intervention 3; 1,291,872 € for PM intervention 4 and 83,818 € for PM intervention 5. All together bring in

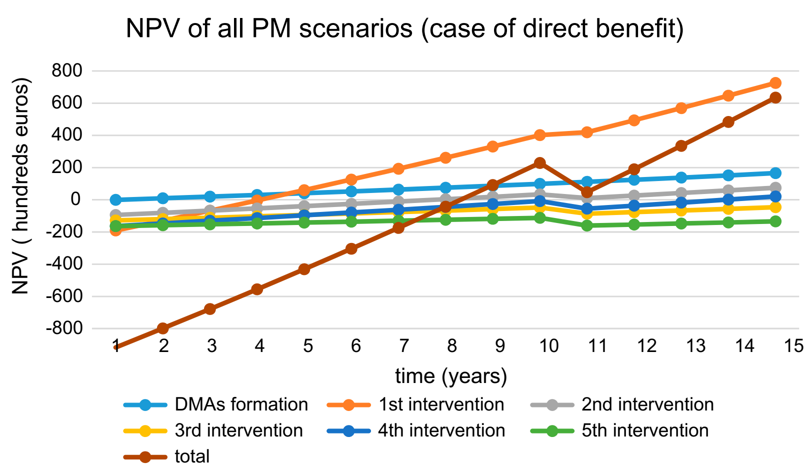

Fig. 5. Evolution of the NPVs of all interventions in case of direct economic benefit.

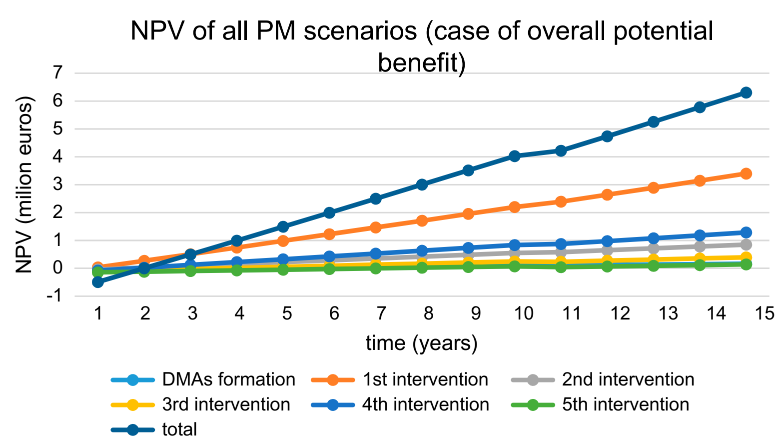

Fig. 6. Evolution of the NPVs of all interventions in case of overall potential economic benefit.

6,370,301 €. According to this intervention, 28 PRVs are required to be installed in total. Fig. 6 presents the gradual evolution of the NPV for each intervention separately and for all of them applied at the same time.

5. Conclusions

In the water distribution network in the city of Kozani, high NRW levels were observed, mainly caused by the high operating pressures, the system was experiencing and the fact that no DMAs were formed. Herein, the proposed application of various alternative PM scenarios was analysed, starting from the simple formation of adequate DMAs and sub-DMAs, to the configuration of other five scenarios based on installing a relatively small number of PRVs in some of the DMAs and sub-DMAs. To select the best combinations of interventions, the NPVs of all PM scenarios were calculated for a period of 15 years. The analysis of the resulting economic benefits proved what was expected from the beginning that is the fact that the first cost to be reduced is the cost of energy consumed in all processes of urban water supply (i.e. abstraction, supply, treatment, storage and distribution) apart from the administration. However, the benefits resulting from the system's pressure reduction in terms of new leaks and breaks frequency reduction are much greater. These benefits are analysed as direct (i.e. reduced maintenance costs of the water distribution process) and indirect (i.e. reduced personnel, insurance and vehicle operation costs related to the repair of mains' failures and pipe services). Considering the type of benefits involved, the total gains (as NPV) after a 15-year period range from 698,873 €, in case only direct benefits are considered, to 6,370,301 € when also indirect benefits are included.

A very important task is the calculation of revenue losses caused by the application of any PM scenario, apart from the costs related to the initial studies necessary, installation, maintenance and replacement. The major revenue loss is caused by the reduction of the pressure-dependent part of the actual water demand affected by the reduction of the operating pressure along with the increase of the water metering errors that also result from the lowered pressure that of the water reaching the water metres. Accurate calculation of the WDS's water balance is required along with an estimation of how much of the billed water use is pressure-dependent. This rate will determine the major degree of reduction in the water quantities recorded by the water metres and therefore the degree of revenue losses. These losses were separately calculated for each PM scenario checked for Kozani's WDS and only for the first year following the PRVs' installation were estimated to each 247,361 €. The most efficient and favourable impact on both actual losses and real consumption has been identified to be PM. It is an effective method for recovering a large proportion of NRW since the key benefits of PM are not restricted only to water losses reduction. When applying lower pressures in the system, burst frequencies of mains, service connections and ageing of pipes, resulting in longer lifetimes are also reduced, and ultimately, the economic lifetime of entire system increases.

References

[1] R. Puust, Z. Kapelan, D. Savic, T. Koppel, A review of methods for leakage management in pipe networks, Urban Water J. 7 (2010) 25–45.

[2] M. Farley, S. Trow, Losses in Water Distribution Networks: A Practitioner's Guide to Assessment, Monitoring and Control, IWA Publishing, London, 2003.

[3] J. Thornton, R. Sturm, G. Kunkel, Water Loss Control, second ed., McGraw-Hill, New York, NY, 2008.

[4] M. Babel, M. Islam, A. Gupta, Leakage management in a low-pressure water distribution network of Bangkok, Water Sci. Technol. Water Supply 9 (2009) 141–147.

[5] R. McKenzie, H. Mostert, T. De Jager, Leakage reduction through pressure management in Khayelitsha: Two years down the line, Water SA 30 (2004) 13–17.

[6] Z. Pilipovic, R. Taylor, Pressure management in Waitakere City, New Zealand—A case study, Water Sci. Technol. Water Supply 3 (2003) 135–141.

[7] I. Karadirek, S. Kara, G. Yilmaz, A. Muhammetoglu, H. Muhammetoglu, Implementation of hydraulic modelling for water-loss reduction through pressure management, Water Resour. Manage. 26 (2012) 2555–2568.

[8] M. Girard, R.A. Stewart, Implementation of pressure and leakage management strategies on the Gold Coast, Australia: Case study, J. Water Resour. Plann. Manage. 133 (2007) 210–217.

[9] M. Fantozzi, A. Lambert, Including the effects of pressure management in calculations of Short-Run Economic Leakage Levels, in: Water Loss 2007, Specialized Conference Proceedings, IWA, Bucharest (Romania), 2007.

[10] J. Thornton, A. Lambert, Managing pressures to reduce new breaks, Water 21(8) (2006) 24–26.

[11] Á. Martínez-Codina, L. Cueto-Felgueroso, M. Castillo, L. Garrote, Use of pressure management to reduce the probability of pipe breaks: A Bayesian approach, J. Water Resour. Plann. Manage. (2015), doi: 10.1061/(ASCE)WR.1943-5452.0000519.

[12] K. Diao, Y. Zhou, W. Rauch, Automated creation of district metered area boundaries in water distribution systems, J. Water Resour. Plann. Manage. 139 (2013) 184–190.

[13] A. Di Nardo, M. Di Natale, G. Santonastaso, V. Tzatchkov, V. Alcocer-Yamanaka, Water network sectorization based on graph theory and energy performance indices, J. Water Resour. Plann. Manage. 140 (2014) 620–629.

[14] S. Alvisi, M. Franchini, A heuristic procedure for the automatic creation of district metered areas in water distribution systems, Urban Water J. 11 (2014) 137–159.
[15] F. De Paola, N. Fontana, E. Galdiero, M. Giugni, D. Savic, G. Sorgenti deghli Uberti, Automatic multi-objective sectorization of a water distribution network, Procedia Eng. 89 (2014) 1200–1207.
[16] R. Gomes, A.S. Sá Marques, J. Sousa, Identification of the optimal entry points at District Metered Areas and implementation of pressure management, Urban Water J. 9 (2012) 365–384.
[17] A. Lambert, M. Fantozzi, J. Thornton, Practical approaches to modeling leakage and pressure management in distribution systems—Progress since 2005. Proceedings of the 12th International Conference on Computing and Control for the Water Industry-CCWI2013, Perugia, Italy, 2013.
[18] V. Kanakoudis, K. Gonelas, M. Patelis, Developing water pressure management scenarios to cut down the real losses in the water distribution system of Kozani, Greece, Proceedings of the 12th International Conference on Protection & Restoration of the Environment-PRE12, Skiathos, Greece, 2014.
[19] V. Kanakoudis, K. Gonelas, Developing a methodology towards full water cost recovery in urban water pipe networks, based on the “user pays” principle, Procedia Eng. 70 (2013) 907–916.