Reaching economic leakage level through pressure management

K. Gonelas and V. Kanakoudis

ABSTRACT

High non-revenue water (NRW) values as a percentage of system input volume form a serious problem that many water utilities worldwide have to confront nowadays. There are ways to mitigate the effect by adopting strategies with short- and long-term results. Water pressure management (PM) is one of the most efficient and effective NRW reduction strategies. To calculate pressure management of economic level of leakage (ELL), several steps have to be taken, such as full water costing, calculation of economic benefits and losses of PM interventions and definition of the related investment's break-even point. In this paper, the results of these three procedures required to define the ELL level are analyzed, in order to present the way they are linked together. The water distribution system of Kozani city (in Northern Greece) is used as the case study network. The results of both the net present values PM implementation results and the investment's break-even estimation are analyzed.

Key words | district metered areas, non-revenue water, pressure management

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INTRODUCTION

During the last decade, water utilities have moved towards the implementation of pressure management (PM) to reduce the high non-revenue water (NRW) values from which their systems are suffering. By reducing excessive pressure, real loss components (background leakage, reported and unreported leaks) are reduced. In fact, the volume of the last two components is reduced not only due to pressure reduction, but also as bursts frequency (breakage rate) is being reduced also. New breaks rate depends on the maximum operating pressures of the network. District metered area (DMA) implementation and pressure reducing valves (PRVs) installation are strong leakage management tools with positive effects on water systems management (Farley & Trow 2003; Thornton *et al.* 2008; Puust *et al.* 2010). PM implementation leads to reduced leakage flow rates and bursts repair costs both for mains and service connection pipes (McKenzie *et al.* 2004; Babel *et al.* 2009). The anxiety of revenue loss related to a network's reduced operating pressure and the difficulty to predict the economic benefits and losses, prevented water utilities implementing PM projects (Kanakoudis & Gonelas 2015a). There have been several efforts recently promoting pressure and leakage management as policies achieving both water savings and conservative demand and also delaying infrastructure expansion (Girard & Stewart 2007; Fantozzi & Lambert 2007). A PM project starts by dividing the entire network into smaller 'hydraulically isolated' areas (DMAs) for easier and more effective/efficient management and inspection. PRVs are installed near DMA entering nodes to restrain excessive pressure and thus ultimately reduce real losses.

Optimal formation of DMAs and installation of PRVs can be achieved by testing scenarios developed in a calibrated and validated network's hydraulic simulation model. DMA formation is a multi-dimensional problem and there have been many efforts to solve it using optimization techniques (Deuerlein 2008; Di Nardo *et al.* 2013). Searching for the optimal (in terms of cost–benefit analysis) level of PM investments is a complex process too. PM's economic level of leakage (ELL) estimation requires calculation of the full water cost through

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breakdown of the water utility's Balance Sheet. Then the economic benefits and losses caused separately by each PM intervention should be safely calculated. Finally the break-even of the investment must be defined too. This methodology is analyzed and implemented in the water distribution system (WDS) of the city of Kozani's WDS. The formation of 24 DMAs and installation of 12 PRVs were simulated in the WDS's hydraulic model. The impact of five PM scenarios was estimated and the net present value (NPV) of PM implementation was calculated considering both economic benefits and costs (revenue losses considered too) arising from the network's pressure reduction. Break-even of the PM investments proved to be crucial for estimating the EARL (economic annual real losses) level. The NPVs and the break-even of the PM investments were all determined. For a more accurate analysis, two economic benefits approaches were applied, the direct benefit approach (resulting from reduced energy, treatment and maintenance costs) and indirect benefit approach (resulting from reduced personnel, insurance and vehicles operation costs). Finally, the calculation of the system input volume (SIV) reduction rate depending on the network's operating pressure is presented.

METHODOLOGY

To safely calculate the ELL for any PM scenario, there are three prerequisites. At first it is necessary to correctly analyze the full water cost demonstrating its variation during the PM scenario implemented. Then, the reliable calculation of economic losses and benefits resulting from the PM scenario must follow. Finally, the EARL levels must be safely assessed, defining the balancing point between PM's total costs and revenues.

Full water costing

WFD 2000/60/EC requires the calculation of the three full water cost components (direct, resource and environmental cost – DC, RC and EC). In 2013, the authors presented a respective methodology, suggesting the full analysis of the water utility's Balance Sheet in various sub-costs (Kanakoudis & Gonelas 2013). Based on that methodology, the Balance Sheet is split into 11 operation and maintenance sub-costs and three capital sub-costs (Table 1). Furthermore, each one of these sub-costs is allocated to the seven urban water procedures (Table 2). This water cost breakdown in parts, helps in the calculation of economic benefits and losses, resulting from PM interventions.

Table 1 | Cost categories included in a water utility's balance sheet

Operation & maintenance costs
Personnel cost
Energy cost
Leasing and rents
Maintenance cost
Consumables cost
Insurance cost
Telecommunications cost
Vehicles operating cost
Taxation cost
Financial cost
Management cost
Capital costs
New investments
Depreciation cost
Capital (opportunity) cost

Table 2 | The most common 'procedures' included in an urban water supply chain

Urban water procedures
Abstraction
Supply
Raw water treatment
Storage
Distribution
Drainage & sewage water treatment
Administration

Economic benefits, expenditures and revenue losses resulting from a PM scenario

Regarding PM results, it was found that due to the SIV reduction, the energy cost of abstraction, supply, treatment, storage and distribution of water is reduced. Raw water treatment consumables cost (chemicals, chlorine, etc.) is reduced too. Reduction of a network's pressure results in fewer pipe breaks and therefore lower maintenance and related infrastructure replacement costs. Lambert *et al.* (2013) estimated the correlation between the decreased maximum pressure in a network and the reduced rate of new breaks. Subsequently, both the personnel and vehicle operation costs needed to repair the decreased number of breaks are reduced too. Kanakoudis & Gonelas (2015a) proposed equations that calculate several economic benefits resulting from new-break rate reduction due to pressure reduction.

Equipment purchase and installation costs occurring at the beginning of the investment are accounted as PM expenditures. Other expenditures are PM interventions management and maintenance costs and cost of studies (Kanakoudis & Gonelas 2015a). Pressure reduction results in revenue losses for the water utility due the reduced metered water volume (as a part of it, is pressure dependent). These revenue losses are calculated utilizing the network's hydraulic model, which is able to simulate the nodal consumptions as pressure dependent. This means that the pressure dependent rate of billed water consumption volume should be determined first.

Calculating the investment's break-even

The economic impact of dividing the network into DMAs and installing PRVs is assessed using the network's hydraulic model and appropriate equations developed. At first the NPV of the costs and benefits resulting from any intervention applied are assessed. The EARL level for a requested period is calculated when the cost of the intervention applied plus the potential economic losses that follow (e.g. revenue losses) equal the benefits gained from this intervention for the study period (NPV considered for all values). Figure 1 shows that this NPV may not get to zero for a given study period. As a result, further PM interventions should be applied to reach the investment's zero point (break-even). PM interventions are prioritized based on a cost–benefit analysis, forming a list of potential actions. Thus the interventions at the top of the list have higher financial benefits, while the next ones drive to less profitable outcomes. From some point after, the interventions cost more than the economic benefits they bring along. However as a large profit is gathered by the interventions initially applied (from the top of the list), and as the ultimate goal is to reduce the pressure as much as possible (up to the brake-even point of the cumulative investment), several additional interventions might be required so that the total economic footprint will get to zero. It is quite time-consuming to simulate (hydraulic model) new interventions to the point where NPV is zeroed. To overcome this obstacle, Equation (1) was developed (Kanakoudis & Gonelas 2015a) correlating the amount of money available (from the initial profitable interventions) to use it in applying further PM actions to further reduce the SIV, until the NPV of the entire investments gets to zero.

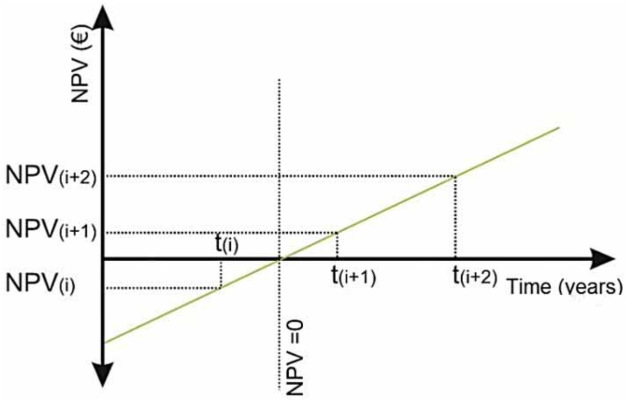

Figure 1 | NPVs of the initial PM interventions over time.

$$R_{\mathrm{SIV}} = \begin{cases} c_1 \times \ln(C_{\mathrm{TOTAL}}) + c_2,\ \gamma\iota\alpha\, C_{\mathrm{TOTAL}} < I'_{\mathrm{PM}} \\ (c_1 \times \ln(C_{\mathrm{TOTAL}}) + c_2) \times {C_{\mathrm{rd}}}^{C_{\mathrm{TN}}}, \gamma\iota\alpha I'_{\mathrm{PM}} < C_{\mathrm{TOTAL}} < I''_{\mathrm{PM}} \\ (c_1 \times \ln(C_{\mathrm{TOTAL}}) + c_2) \times {C_{\mathrm{rd}}}^{I''_{\mathrm{PMN}}},\ \gamma\iota\alpha\, I''_{\mathrm{PM}} < C_{\mathrm{TOTAL}} \end{cases} \tag{1}$$

where R_{SIV} is SIV reduction [m^3], C_{TOTAL} is the total cost of the interventions [M€] for achieving the specific SIV reduction, c_1 and c_2 are the coefficients resulting from the correlation, I'_{PM} is the total cost of the initial interventions [M€], C_{TN} is an index equal to C_{TOTAL} in integers [M€], I''_{PM} is the cost of interventions beyond which R_{SIV} does not vary [M€], I''_{PMN} is an index equal to I''_{PM} in integers [M€] and C_{rd} is a reduction factor and depends on R_{SIV} caused by the initial interventions.

IMPLEMENTATION

Basic characteristics of Kozani's WDS and its hydraulic model

Kozani city, is the capital city of Kozani County in West Macedonia Region in Greece. The city lies 710 m above sea level. The population of the municipality exceeds 70,000 people. The local water and sewage utility (called DEYAK) serves almost 50,000 people. Kozani's widely spread well-designed WDS covers a huge area, including the entire city and its expansions in more than ten suburbs. The total annual SIV equals 6,921,387 m^3. 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 (Figure 2).

DEYAK's full water costing

The urban water supply chain was separated into seven successive components (water abstraction, water supply, raw water treatment, water storage, water distribution, sewage water treatment and administration). There are also 14 potential cost categories involved in these components. In the past, several hidden environmental and resource costs were falsely considered as parts of the DC, while parts of the water abstraction and supply related costs should be considered Resource Costs as the nearby mining activities of the Greek Public Power Company forced DEYAK to seek more expensive water resources elsewhere. Figure 3 presents the full water cost of each one of the seven successive components of the urban water supply chain, along with the total full water cost for DEYAK.

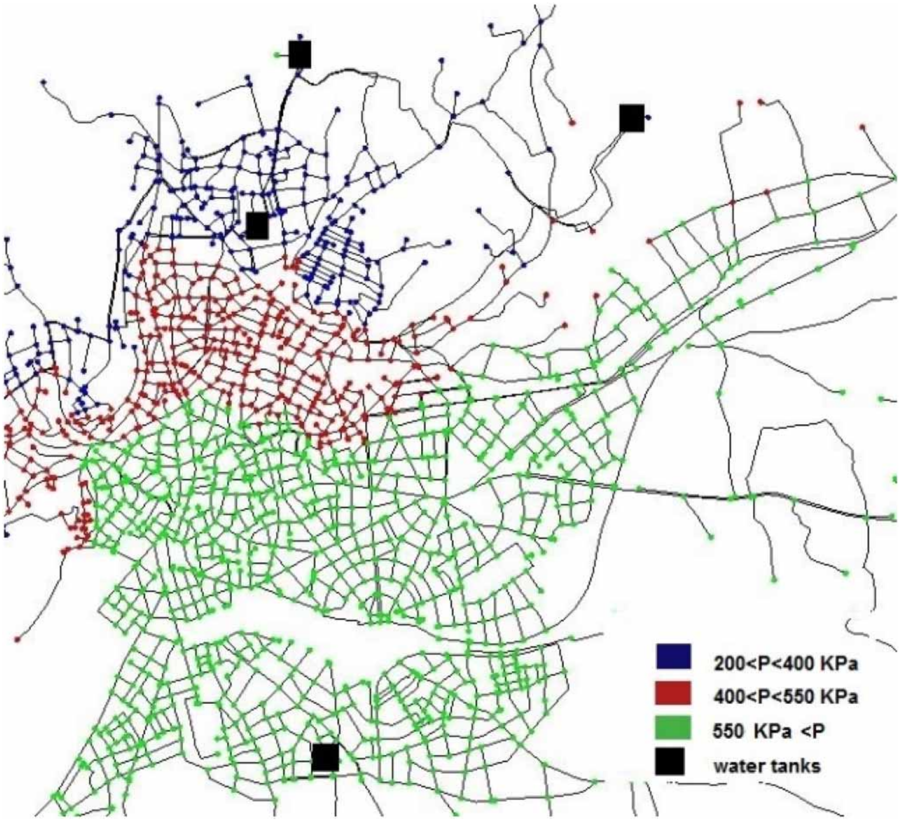

Figure 2 | Kozani city WDS pressure zones & water tanks (Kanakoudis & Gonelas 2015a). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2015.181.

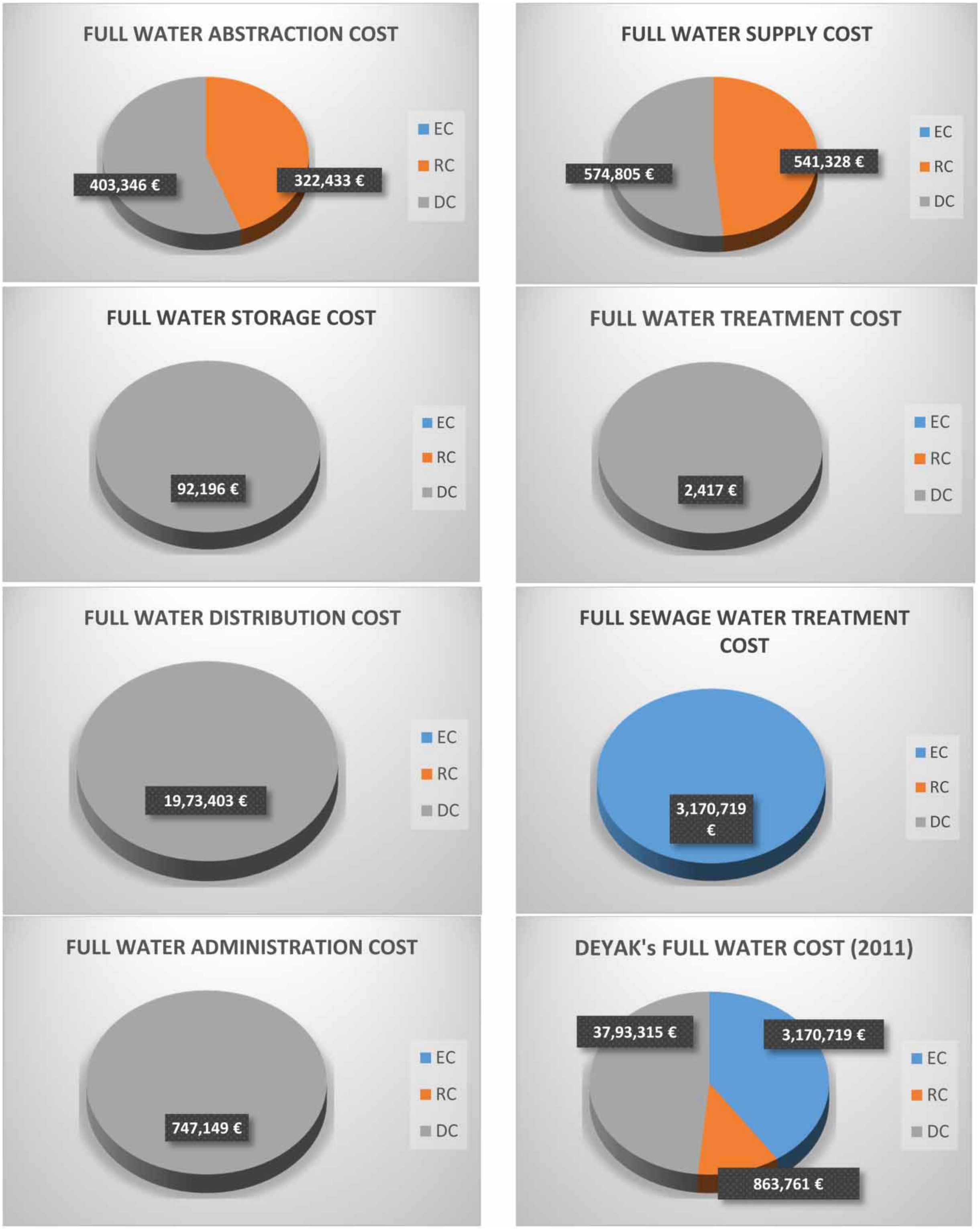

Figure 3 | Full water cost of each of DEYAK's 7 urban water sub-systems (and total full cost). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2015.181.

Implementation of the PM scenarios and calculation of their NPVs

Kozani's WDS was divided into 24 DMAs (Kanakoudis *et al.* 2014). The basic criteria taken into account were hydraulic efficiency and meeting firefighting requirements for each DMA. Five basic PM interventions/scenarios were prioritized and successively implemented. These scenarios were mainly based on installing a number of PRVs at the entrances of some DMAs (Kanakoudis & Gonelas 2015a). The application of the nth intervention implies the implementation of the $(n-1)$th intervention. Table 3 shows the reduction of the SIV caused by forming the DMAs and each one of five PM successive interventions.

The NPV of each PM scenario was calculated following two economic benefit definition approaches. According to the first one, only the PM's direct benefits (reduced energy, treatment and maintenance costs), were considered as positive financial outputs (Figure 4). The SIV for 2011 was 6,921,387 m^3, while after all PM scenarios were implemented it dropped to 4,645,439 m^3. According to the second approach, economic benefits also included the reduction of personnel, insurance and vehicles operation costs related to breaks and leaks repairing (Figure 5). These costs are considered as indirect benefits.

Break-even calculation

The EARL after a 15-year period of implementation was chosen to be the decisive criterion by which to judge each PM scenario. Nevertheless, the results presented (Figures 4 and 6) proved that the NPV doesn't get to zero in the 15-year study period. Consequently, the necessary interventions should be formed that way so that the total NPV is zeroed. Table 4 presents the costs of the initial five PM scenarios, while the graph shown in Figure 6 was used to calculate the first branch of Equation (2). Then, the other two branches of Equation (2) were calculated (Kanakoudis & Gonelas 2015b), in order to be applicable for higher funding available for PM interventions.

where R_{SIV} is the SIV reduction (Mm^3); C_{TOTAL} is the interventions total cost (M€) to achieve the SIV reduction; and C_{TN} is an integer that indicates to which interval (of M€) C_{TOTAL} is having values between 2 and 9.

Equation (2) calculates the annual SIV reduction when PM reduces the current annual real losses (CARL) to the EARL levels. Table 5 presents the reduced SIVs for different NPV time reference periods and for direct and overall (direct and indirect) economic benefits. When overall economic benefits are considered, more PM interventions are cost-effective. Thus, overall economic benefit consideration increases the profit of each PM intervention, so there is more cash available for further (new) PM interventions to be applied, resulting in higher SIV reduction.

Correlation of Q_{REV} reduction as % of R_{SIV} in relation to pressure

During PM implementation, the expected reduction of the SIV (R_{SIV}) should be estimated. To calculate the investment's break-even point, it is necessary to know how much of the R_{SIV} is billed consumption. The latter depends on SIV variation already calculated and the network's operating pressure. For the initial operating pressure, it is easy (using the hydraulic model) to calculate the part of the R_{SIV} that is billed metered consumption (for Kozani it reached 22.5%). As operating pressure decreases, the R_{SIV} part being billed (consumption) reduces too. When the pressure drops, then certain water consumption activities, such as car washing or garden watering, take longer to carry out as they are volume dependent water uses. Trying to quantify this phenomenon, the graph of Figure 7 was developed, leading to Equation (3), linking the part of the R_{SIV} that is billed metered consumption to the final operating pressure applied. Table 6 presents all SIV components when PM reduces the real losses at EARL levels

$$\frac{Q_{\mathrm{REV}}}{R_{\mathrm{SIV}}} = 0,0752 \times e^{0{,}0019 \times P} \tag{3}$$

where R_{SIV} is the SIV reduction (m^3); Q_{REV} is revenue water volume (m^3); P is pressure (kPa).

$$R_{\mathrm{SIV}} = \begin{cases} 413.992 \times \ln(C_{\mathrm{TOTAL}}) + 3.344.000, & \gamma\iota\alpha\ C_{\mathrm{TOTAL}} < 922.914 \\ (413.992 \times \ln(C_{\mathrm{TOTAL}}) + 3.344.000) \times 0,986^{C_{\mathrm{TN}}}, & \gamma\iota\alpha\ 922.914 < C_{\mathrm{TOTAL}} < 9.000.000 \\ (413.992 \times \ln(C_{\mathrm{TOTAL}}) + 3.344.000) \times 0,986^{9}, & \gamma\iota\alpha\ 9.000.000 < C_{\mathrm{TOTAL}} \end{cases} \tag{2}$$

Table 3 | Water savings after applying PM scenarios in Kozani's WDS (base year: 2011)

Water savings					
PM interventions	**(m^3/year)**	**% SIV**	**PM interventions**	**(m^3/year)**	**% SIV**
DMA formation	125,112	1.71	3rd intervention	156,476	2.26
1st intervention	1,460,786	19.97	4th intervention	164,954	2.38
2nd intervention	231,603	3.32	5th intervention	137,018	1.98
			Total	2,275,948	31.65

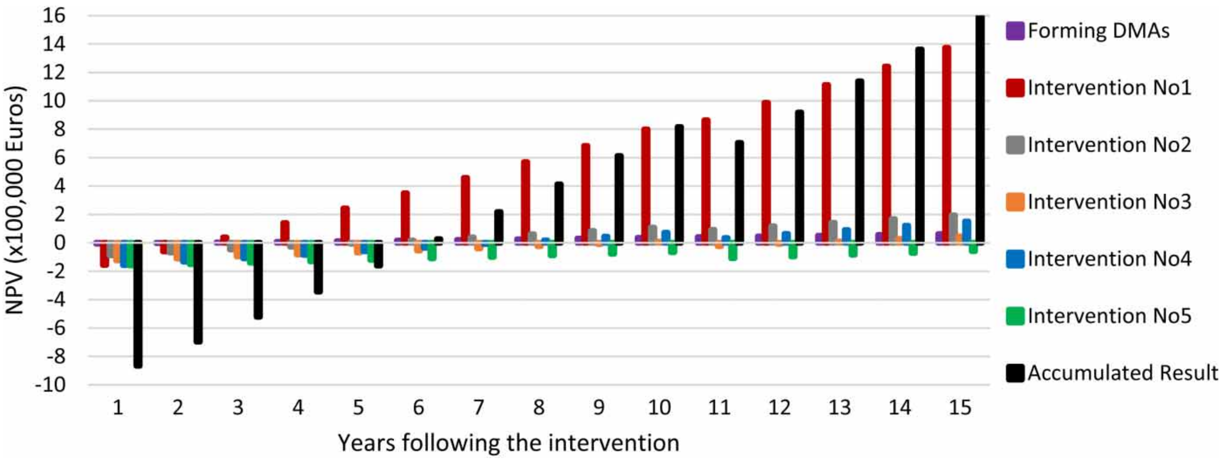

Figure 4 | NPV evolution in case of direct economic benefit for each intervention. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2015.181.

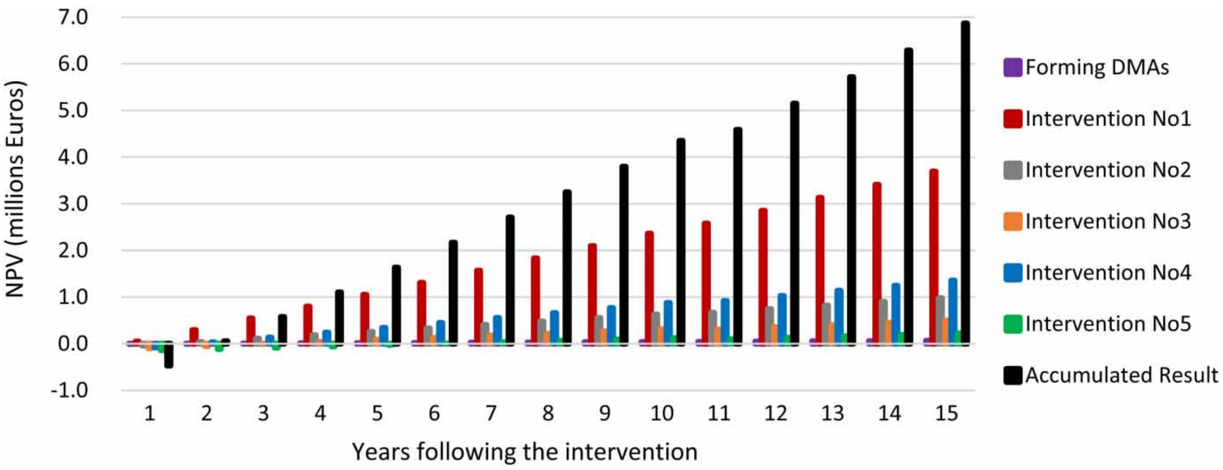

Figure 5 | Evolution of NPVs of all interventions in case of overall potential economic benefit. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2015.181.

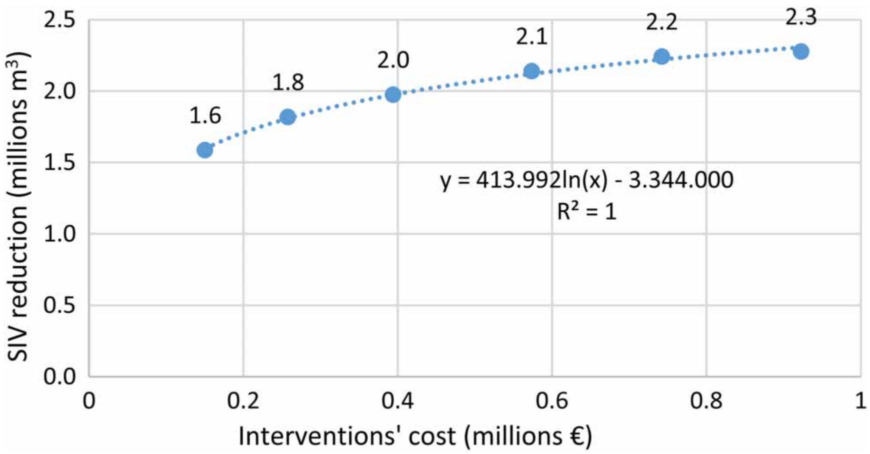

Figure 6 | Interventions cost related to SIV reduction.

Table 4 | Data of interventions costs and SIV reductions (Kanakoudis & Gonelas 2015b)

Interventions	SIV (m^3/day)	SIV reduction (m^3/day)	SIV reduction (m^3/year)	Cost per intervention (€)	Accumulated cost after each intervention (€)
1st intervention	12,405.58	4,345.11	1,585,965	150,240 €	150,240 €
2nd intervention	11,771.05	4,979.64	1,817,569	107,427 €	257,667 €
3rd intervention	11,342.35	5,408.34	1,974,044	136,408 €	394,075 €
4th intervention	10,798.08	5,952.61	2,172,703	179,674 €	573,749 €
5th intervention	10,423.20	6,327.49	2,309,534	349,165 €	922,914 €

Table 5 | DEYAK's SIV reduction for 2011 (when CARL equals EARL)

NPVs time reference	SIV reduction (m^3) Direct economic benefit	SIV reduction (m^3) Overall economic benefit
5-years	2,241,167	2,650,703
10-years	2,534,420	2,815,867
15-years	2,644,605	2,881,703

RESULTS AND DISCUSSION

DEYAK full water cost for 2011 (base year) was equal to 7,827,795 €, while the RC was equal to 863,761 €. The breakdown of DEYAK's Balance Sheet costs led to a more reliable calculation of economic benefits and losses related to PM scenarios applied. DMA formation and PRV installations were simulated in the network's hydraulic model. Then, the annual economic benefits and expenses were calculated for different NPV time reference periods. Reduction of burst frequency due to the reduced maximum network operating pressures led to reduced pipe breaks and therefore to direct maintenance cost reduction. NPVs of the interventions were calculated for two different approaches of economic benefit definition (direct and overall = direct + indirect). Comparing the two approaches above, NPV is almost five times higher when the overall economic benefits are considered. The NPVs of the PM scenarios after the 15-years study period range from 1,591,415€ (when only direct benefits are considered), to 6,864,564€ (when also indirect benefits are included too).

The cost of the initial five PM interventions (922,914 €) and the resulting reduction of the SIV (2,309,534 m^3) helped in finding the break-even of these PM investments. Using the initial interventions data and Equation (1), the reduction of SIV was calculated for any amount of cash available for PM

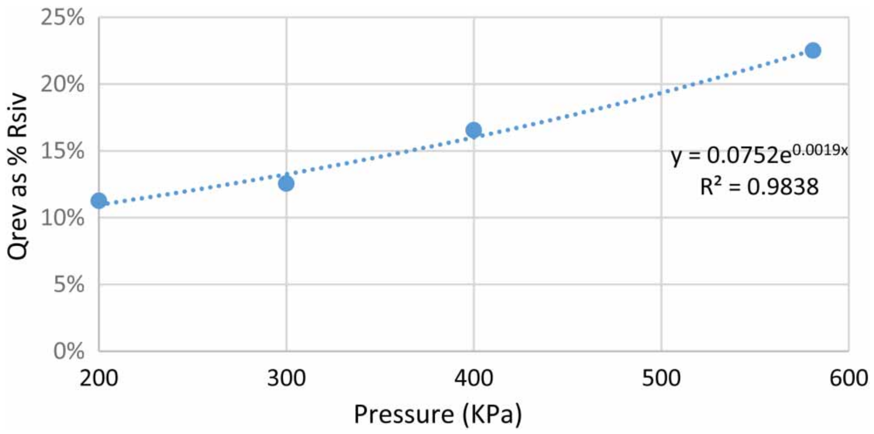

Figure 7 | Revenue water volume as % of R_{SIV} related to pressure.

Table 6 | SIV components when PM reduces real losses at EARL levels (NPV of 15-year time period)

	Water volumes	
SIV components	**Initial Status**	**PM implementation in EARL level (direct and indirect benefit)**
SIV	6,921,387	4,039,684
Billed consumption	2,555,472	2,159,489
Authorized non-billed consumption	138,428	116,978
Illegal use	69,214	58,489
Reading errors	127,774	107,975
Under-registration	127,774	149,405
Real losses	3,902,727	1,447,349

interventions. The reduction of the SIV resulting from the PM interventions (up to the investment's break-even point) for the 15-year study period was calculated equal to 2,644,605 m^3 and 2,881,703 m^3 for considering direct and overall economic benefit respectively. Concerning the utility's revenue losses due to the SIV reduction (related to the pressure dependent demand), it varies with the network's operating pressure. As this pressure decreases, the rate of the reduced invoiced consumption gets lower.

CONCLUSIONS

The most efficient impact on both real losses and billed consumption has been identified to be PM (apart from the obvious but nevertheless extremely costly one of the assets' replacement). To fully estimate the ELL of any presume management scenario, it is necessary first to calculate the full water cost, estimate the economic benefits and losses caused separately by each PM intervention and calculate the investment's break-even point. When applying lower pressures in the system, burst frequencies of distribution mains and service connections pipes are reduced. In Kozani's WDS, high values of water losses were observed, mainly due to the network's high operating pressures. The economic benefits and losses of the proposed PM interventions (and DMA formation) were calculated. PM interventions were virtually (in the hydraulic model) implemented by installing a relatively small number of PRVs in specific DMAs. NPVs of 6 (DMA formation +5 PM scenarios) proposed interventions reached high values. The maximum time period reference for NPV calculation was 15 years. It was observed, as expected, that for longer NPV time period calculation, the investment's profit was getting higher, resulting in higher real losses reduction.

The calculation of revenue loss caused by the reduction of the pressure-dependent part of the actual water consumption is crucial. This will determine the reduction rate of the revenue water and therefore the utility's revenue losses level. However, NPV calculation is important during the estimation of the EARL level. In the present paper, a graphical solution of the problem detecting the break-even of the PM interventions was developed, which led to high SIV reduction. It is very important, during the quantification of the results, to calculate the R_{SIV} rate which expresses revenue water.

REFERENCES

Babel, M., Islam, M. & Gupta, A. 2009 Leakage management in a low-pressure water distribution network of Bangkok. *Water Sci. Technol.: Water Supply* **9**, 141–147.

Deuerlein, J. W. 2008 Decomposition model of a general water supply network graph. *J. Hydraul. Eng.* **134**, 822–832.

Di Nardo, A., Di Natale, M., Santonastaso, G. F. & Venticinque, S. 2013 An automated tool for smart water network partitioning. *Water Resour. Manag.* **27** (13), 4493–4508.

Fantozzi, M. & Lambert, A. 2007 Including the effects of pressure management in calculations of Short-Run Economic Leakage Levels. In: *Water Loss 2007, Conference Proceedings*, IWA, Bucharest.

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

Girard, M. & Stewart, R. A. 2007 Implementation of pressure and leakage management strategies on the gold coast, Australia: case study. *J. Water Resour. Plann. Manage.* **133**, 210–217.

Kanakoudis, V. & Gonelas, K. 2013 Developing a methodology towards full water cost recovery in urban water pipe networks, based on the 'user pays' principle. *Procedia Engineering* **70**, 907–916.

Kanakoudis, V. & Gonelas, K. 2015a Non-Revenue water reduction through pressure management in Kozani's water distribution network: from theory to practice. *Desal. Water Treat.* **57** (25), 11436–11446.

Kanakoudis, V. & Gonelas, K. 2015b The optimal balance point between NRW reduction measures, full water costing and water pricing in water distribution systems. Alternative scenarios forecasting Kozani's optimal balance point. *Procedia Engineering*, **119**, 1278–1287 (CCWI 2015). http://www.sciencedirect.com/science/article/pii/S1877705815026661.

Kanakoudis, V., Gonelas, K. & Patelis, M. 2014 Developing water pressure management scenarios to cut down the real losses in the water distribution system of Kozani, Greece. In: *Proceedings of the 12th Int. Conf. on Protection & Restoration of the Environment-PRE12*, Skiathos, Greece, pp. 248–255.

Lambert, A., Fantozzi, M. & Thornton, J. 2013 Practical approaches to modeling leakage and pressure management in distribution systems – progress since 2005. In: *Proceedings of the 12th Int. Conf. on Computing and Control for the Water Industry-CCWI2013*, Perugia, Italy.

McKenzie, R., Mostert, H. & De Jager, T. 2004 Leakage reduction through pressure management in Khayelitsha: two years down the line. *Water SA* **30**, 13–17.

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

Thornton, J., Sturm, R. & Kunkel, G. 2008 *Water Loss Control*, 2nd edn. McGraw-Hill, New York.

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