Practical Paper

Ex-post evaluation of a water distribution network upgrading project

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ABSTRACT

The paper presents the ex-post evaluation of a project that a Water Utility implemented in its water distribution network. The project included installation of PRVs (Pressure Reducing Valves) and launching of a Public Awareness Campaign, in order to decelerate the pipes' brake rates (by dividing the whole system into pressure zones); and decrease the urban water consumption. Break rate forecasting models are developed, using the Water Utility's records, in order to determine each pipe's optimum replacement time, based on the Present Value of all types of costs related to a pipe break. The results are compared to those of similar projects implemented in other networks having similar characteristics. Finally, the project is evaluated based both on its environmental and financial (money savings) impacts (through a cost-benefit analysis).

Key words | cost-benefit analysis, water distribution network upgrading project

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INTRODUCTION

Water being lost due to leaks, breaks and lack of an effective Water Demand Management Policy is one of the most crucial problems that Water Utilities are facing today. Although studies worldwide proved that water losses rates in well maintained networks can be less than 10% of the total water supplied, in Greece, the leaks/breaks-related water losses are nearly 30% to 40%, in big and small cities, respectively (Kanakoudis & Tolikas 2001). Research is nowadays being focused on finding ways to prevent, not only breaks but also leaks from occurring, as leaks compared to breaks, may have smaller water losses rates, but they result in greater water losses volumes, due to the fact that it is not easy to detect them and thus last more. The most effective way to reduce the number of leaks/breaks incidents are: on time replacement of a pipe, when its economical lifetime has expired and its repair is just money loss; and implementation of cost-effective lifesaving intervention projects.

OPTIMUM REPLACEMENT TIME OF A PIPE

To determine the optimum replacement of a pipe, two things are mainly necessary: a) to develop pipe-break rates forecasting models; and b) to estimate all the various kinds of costs related to a break.

Pipe-break rates forecasting models

The first attempts to develop pipe-break rates forecasting models through statistical analysis of failure records, took place in late 70s. At the same time experts started to study the several parameters of a pipe break (Lane & Buehring 1978). In the following years, studies successfully combined pipe break rates with the pipe's size, pressure conditions, exterior loads and neighboring conditions (Clark et al. 1981). Some studies showed that break rates were not as strongly correlated to the age of the pipe as it was initially supposed (O'Day 1982). Other more detailed ones, regarding the quality of the failure records, revealed that the type/rate of

a pipe break is strongly correlated to the pipe's size and material (Kettler & Goulter 1985). In 1988, Goulter and Kazemi, proved the time and space clustering of breaks near an initial failure location, using the data available for the city of Winnipeg, Canada (Goulter & Kazemi 1988).

Through all these years and efforts, several pipe break rate forecasting models have been developed. The present study uses the exponential model:

$$N(t) = N(t_0) \cdot e^{A(t-t_0)} \tag{1}$$

where,

t the time in years,
$N(t)$ the number of pipe breaks per km in year t,
t_0 the actual installation date of a pipe,
A the growth rate coefficient (1 year^{-1}).

This model was initially presented by Walski & Pelliccia (1982) and further developed by Kanakoudis & Tolikas (2001), in order to utilize the results of other studies (Shamir & Howard 1979; Clark & Stevie 1981; Clark & Goodrich 1989; Goulter et al. 1993; Cabrera et al. 1995). The model takes into account the pipe's installation date, as the exact installation time (t_0) or alternatively the mean installation time for each pipe regarding its material, use, size and type, is required during the model development process.

Pipe breaks and the related costs

A pipe's replacement cost includes general expenses and abnormal costs that can be safely determined considering the pipe's material, length, size and installation site (road/pavement), through analytical tables. On the contrary, a pipe's repair cost is difficult to accurately determine as it depends on the characteristics of the break (magnitude/significance) and the repairing method applied. The total repair cost includes: a) costs directly related to the repair works (labour, transport, equipment, repairing materials, landscaping, supervision, general, abnormal costs); and b) costs that quantify the effects of the break related to the Water Utility and its customers. These costs result from: a) the expenses of the Utility regarding water intake/treatment/supply of the water being lost during breaks (non reciprocal costs); and b) that during the repairs, the Utility fails to satisfy the water needs resulting in lost revenues; fire extinguishing water supplied pressure fails; damages to third parties, along with public annoyance and dissatisfaction (social cost), occur. This cost can be two (delivery pipes) to four (water mains) times the actual repair cost (Kanakoudis & Tolikas 2001).

Determining the optimum replacement time of a pipe

The analysis takes place assuming that the pipe age-break function is the exponential one (Equation (1)) referring to a specific type of break (its restoration time does not vary with time). These assumptions ensure that the pipe's length involved in a break, its repair and the replacement costs do not vary with time, resulting in a constant repair unit cost UC_{Rr} (€ per Km). The repair cost of breaks in year t is thus:

$$C_{Rr}(t) = UC_{Rr} \cdot N(t) = UC_{Rr} \cdot N(t_0) \cdot e^{A(t-t_0)} \tag{2}$$

If t_p is the present year, then:

$$PV[C_{Rr}(t)] = \frac{C_{Rr}(t)}{(1+R)^{(t-t_p)}} = \frac{UC_{Rr} \cdot N(t)}{(1+R)^{(t-t_p)}}$$

$$= \frac{UC_{Rr} \cdot N(t_0) \cdot e^{A(t-t_0)}}{(1+R)^{(t-t_p)}} \tag{3}$$

where R is the mean annual rate of inflation. Considering that the replacement takes place in year t_r, then the present value of the total cost for the previous repairs $t_r - t_p$ is:

$$PV\left[\sum C_{Rr}(t)\right] = \sum_{t=t_p}^{t_r} \frac{C_{Rr}(t)}{(1+R)^{(t-t_p)}}$$

$$= \sum_{t=t_p}^{t_r} \frac{UC_{Rr} \cdot N(t_0) \cdot e^{A(t-t_0)}}{(1+R)^{(t-t_p)}} \tag{4}$$

The replacement cost has a constant unit value UC_{Rm} (€ per Km) and present value:

$$PV[C_{Rm}(t_r)] = \frac{UC_{Rm}}{(1+R)^{(t-t_p)}} \tag{5}$$

Considering the equations above it is obvious that the present value of the total repair cost increases with t_r, as an additional term is added each year. On the contrary, the present value of the replacement cost decreases with t_r.

The present value of the total maintenance cost is therefore:

$$PV[C_{tot}(t_r)] = PV\left[\sum C_{Rr}(t_r)\right] + PV[C_{Rm}(t_r)]$$

$$= \left[\sum_{t=t_p}^{t_r} \frac{UC_{Rr} \cdot N(t_0) \cdot e^{A \cdot (t-t_0)}}{(1+R)^{(t-t_p)}}\right] + \frac{UC_{Rm}}{(1+R)^{(t_r-t_p)}} \quad (6)$$

The optimum replacement time t_r^* is:

$$t_r^* = t_0 + \frac{1}{A} \cdot \ln\left[\frac{UC_{Rm} \cdot \ln(1+R)}{UC_{Rr} \cdot N(t_0)}\right] \quad (7)$$

which corresponds to the year in which the annual increase in repair cost is equal to the annual decrease in replacement cost.

The optimum replacement times for the pipes of the case study network

Thessaloniki is the second biggest city in Greece. Its network consists of 1,556 km pipes, serving 1 million customers. The local Water Utility (EYATH) is responsible for the prompt operation of both water supply and water distribution networks. The annual water use is 94 millions m³. The pipes are made of asbestos (58%); cast-iron (16%); PVC (15%); iron (11%). PVC pipes were not further examined as they experience too many breaks regarding their age (installed during 1990), due to the lack of know-how and the fact that some pipes (connection ones) were constructed by the residents themselves in order to satisfy their own needs and not by trained personnel. Unfortunately, these constructions did not meet any quality standards, aiming only at cost reduction instead of quality service. Based on EYATH records (1999–2006), the break age forecasting models developed for each pipe material considering their mean installation dates (cast-iron $t_0 = 1973$; iron $t_0 = 1975$; asbestos $t_0 = 1980$) are:

$$\text{Cast–iron} - y = 0.5258 \cdot e^{0.0341 \cdot x} \quad (8)$$

$$\text{Asbestos} - y = 0.6763 \cdot e^{0.0341 \cdot x} \quad (9)$$

$$\text{Iron} - y = 1.4608 \cdot e^{0.0341 \cdot x} \quad (10)$$

The lack of long time historical break data records resulted in a common break growth rate for all kinds

of pipes (3.47%). This "mean" value agrees with the respective value (3.92%) reported for the Athens network (Kanakoudis & Tolikas 2001). Additionally, the value of the break rate coefficient for cast-iron pipes (0.0341) lies within the margins internationally reported (0.01–0.15) (Shamir & Howard 1979; Clark & Stevie 1981; Walski & Pelliccia 1982). As expected, iron pipes suffered more breaks, compared to asbestos and cast-iron pipes, due to the highly corrosive soil.

The next step was to determine the pipe replacement and repair costs. In Thessaloniki's network, the replacement works are always assigned to the contractor offering the lowest price (public procurement law). Since 2001, the trouble causing pipes (mainly less than 110 mm diameter pipes) are being replaced by 110 mm diameter PVC pipes. Based on EYATH's detailed repairs records, the total mean replacement cost is 39.70 €/m of pipe, while the mean repair cost is 773 €/break. As stated before, studies showed that, in Greece the social cost of a delivery pipe break is two times bigger than the actual repair cost. Therefore, the total mean repair cost of a break in this study is considered to be 2,320 €. Applying Equations (2)–(7) the optimum replacement times for the pipes of EYATH network, when the social cost is considered or not, can be now estimated (Table 1).

Regarding whether the social cost is considered or not, the optimum replacement times for the pipes are 19 and 53 years (iron), 42 and 75 years (asbestos), and 49 and 83 (cast-iron), respectively. These values are sufficiently smaller compared to those reported for the Athens network (232 years for asbestos pipes and 57 years for cast-iron pipes when the social cost is considered) (Kanakoudis & Tolikas 2001), as in Thessaloniki the repair cost growth rate is higher than the replacement cost growth rate, compared to the levels of the respective costs met in Athens. The results showed that EYATH should replace all the iron pipes,

Table 1 | Estimation of the optimal replacement time/year (mean annual inflation rate $R = 5\%$)

	Iron D < 400 mm	Asbestos D < 400 mm	Cast-iron D < 400 mm
t_0 (installation year)	1975	1980	1973
t_r^* (social cost considered)	1994	2022	2022
t_r^* (social cost not considered)	2028	2055	2056

instead of repairing them as their optimum replacement times have already passed. Additionally, although the mean optimum replacement time for the asbestos and cast-iron pipes is 2022, there are some pieces (50 km asbestos and 43 km cast-iron pipes) whose optimum replacement time has passed and should be replaced.

THE PROJECT IMPLEMENTED

In Thessaloniki, until 2000, 65,000–83,000 m^3 of water was daily being lost (30% of the total water supplied). This forced the EU and its relevant Public Works funding departments to "strongly suggest" that EYATH should immediately find a way to minimize these water losses in order for the EU to co-finance the construction of a water supply aqueduct from Aliakmonas River to the city of Thessaloniki. Additionally the EU recommended that a more rational use of the water being transferred should be achieved by implementing an effective water demand management policy. This forced EYATH to carry out extended research, including water pressure monitoring throughout the city, in order to fully understand the way that the network operates. The results revealed that in many network sections the water pressure was much more than 40 m, which is considered satisfactory for an 8 floors building without a boosting device (assuming that one floor has 3 m height and total losses for the building's network 15 m). Based on these findings, the installation of 5 PRVs in specified strategic "nodes" of the network was considered to be the most cost effective thing to do. The PRVs were installed in early 2000.

PROJECT EVALUATION

The first step towards the project evaluation process was to define whether the installed PRVs had a positive impact on the pipe break rates. Prior to the project being implemented, the pipe breaks growth rate was 3.47%. After the installation of the PRVs, the breaks that actually occurred were, by the year 2006, reduced by 42% (1,364 less breaks) compared to the breaks that would have occurred in the same year if no measures were taken (Table 2 and Figures 1, 2). Studies in the specific network showed that the mean water losses during a break are 1,357 m^3 (pipe diameter: 200 mm; water velocity: 2 m/sec; duration of a break: 5 hours; mean values). Thus, the reduction of the pipe breaks from 2000 to 2006 resulted in water savings of 7,224,668 m^3 (5,324 less breaks than those that would have occurred if no measure was taken).

Environmental aspect

The project implemented had an important water saving outcome until 2006 as 7,224,668 m^3 of water was prevented from being lost due to 5,324 less breaks. Additionally, based on EYATH records, until 2000 the annual growth rate of the consumers was 1.5%, resulting in a respective 1% increase of the water consumption. This "water saving" of 0.5% was the result of a "Water Conscience" starting to build up through small scale public awareness campaigns, launched by EYATH in the early 90s. This was also forced by the emerging need for immediate urban water conservation due to the severe water shortage problems that Thessaloniki was facing. Since 2000, the annual growth rate

Table 2 | Pipe breaks (1999–2006)

| Year	Annual breaks (real data)	Annual breaks (if no measures taken)	Additional annual breaks (real data)	Additional annual breaks (if no measures taken)	Annual growth rate of breaks (real data)	Breaks annual reduction rate due to the measures taken
1999	2566					
2000	2655		89		3.47%	
2001	2423	2746	− 232	− 323	− 8.74%	− 11.76%
2002	2248	2840	− 175	− 592	− 7.22%	− 20.85%
2003	2116	2937	− 132	− 821	− 5.87%	− 27.95%
2004	2015	3037	− 101	− 1022	− 4.77%	− 33.65%
2005	1939	3141	− 76	− 1202	− 3.77%	− 38.27%
2006	1884	3248	− 55	− 1364	− 2.84%	− 42.00%
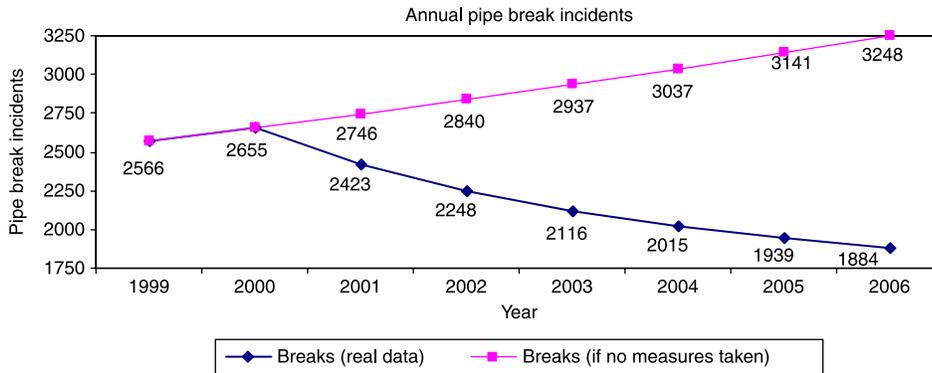
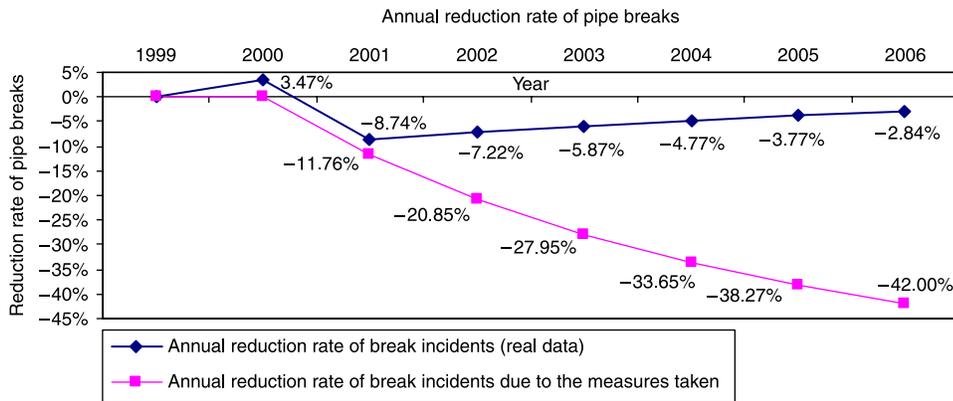**Figure 1** │ Annual pipe breaks (1999–2006).

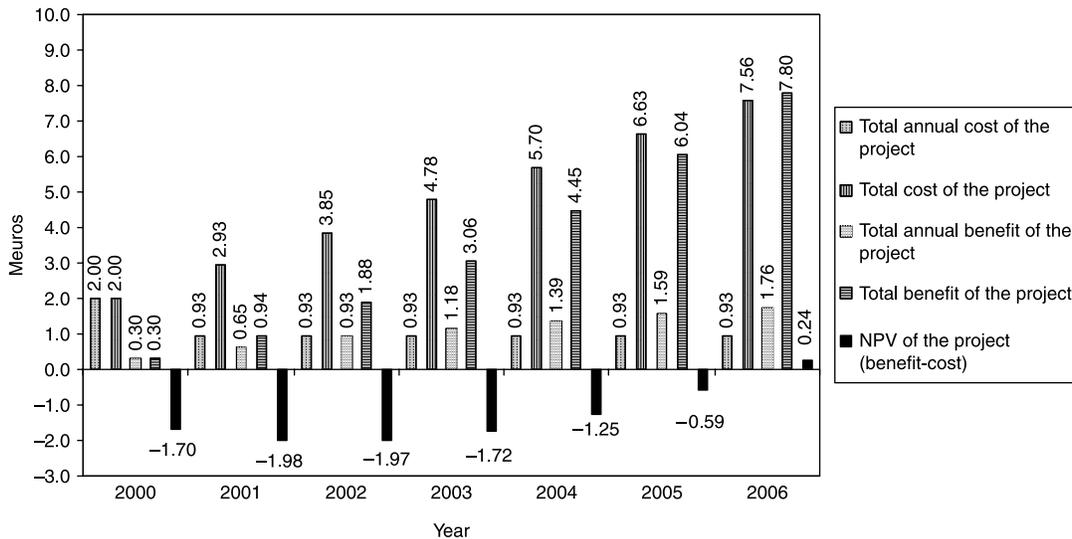**Figure 2** │ Annual pipe break rate (1999–2006).

Figure 3 │ Cost – benefit analysis of the project for the period 2000–2006.

Table 3 | Cost – benefit analysis of the project for the period 2000–2006

Costs[*]	2000	2001	2002	2003	2004	2005	2006
Water not being sold (m^3/year)	1,360,000	1,360,000	1,360,000	1,360,000	1,360,000	1,360,000	1,360,000
Water price (0.60 €/m^3)							
Lost revenues from water not being sold (€/year)	816,000.00	816,000.00	816,000.00	816,000.00	816,000.00	816,000.00	816,000.00
Cost and repair of PRV's installed (€/year)	54,514.00	10,000.00	10,000.00	10,000.00	10,000.00	10,000.00	10,000.00
Fee of the technical consultant (€/year)	1,003,670.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00
Other costs -mainly campaign- (€/year)	126,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00	50,000.00
Total annual cost of the project (€)	**2,000,184.00**	**926,000.00**	**926,000.00**	**926,000.00**	**926,000.00**	**926,000.00**	**926,000.00**
Total cost of the project (€)	**2,000,184.00**	**2,926,184.00**	**3,852,184.00**	**4,778,184.00**	**5,704,184.00**	**6,630,184.00**	**7,556,184.00**
Benefits[*]							
Annual number of breaks not occurred	0	323	592	821	1,022	1,202	1,364
Cost per break -direct- (773 €)							
Cost not paid for pipe breaks repairs (€/year)	0.00	249,679.00	457,616.00	634,633.00	790,006.00	929,146.00	1,054,372.00
Water savings per pipe break not occurred (1,357 m^3)							
Water savings through pipe break reduction (m^3/year)	0.00	438,311.00	803,344.00	1,114,097.00	1,386,854.00	1,631,114.00	1,850,948.00
Cost of water transfer & treatment (0.22 €/m^3)							
Money savings through less water being transferred & treated (€/year)	0.00	96,428.42	176,735.68	245,101.34	305,107.88	358,845.08	407,208.56
Water not being sold (m^3/year)	1,360,000	1,360,000	1,360,000	1,360,000	1,360,000	1,360,000	1,360,000
Money savings through less water being transferred & treated (€/year)	299,200.00	299,200.00	299,200.00	299,200.00	299,200.00	299,200.00	299,200.00
Total annual benefit of the project (€)	**299,200.00**	**645,307.42**	**933,551.68**	**1,178,934.34**	**1,394,313.88**	**1,587,191.08**	**1,760,780.56**
Total benefit of the project (€)	**299,200.00**	**944,507.42**	**1,878,059.10**	**3,056,993.44**	**4,451,307.32**	**6,038,498.40**	**7,799,278.96**
NPV of the project (€)	**− 1,700,984.00**	**− 1,981,676.58**	**− 1,974,124.90**	**− 1,721,190.56**	**− 1,252,876.68**	**− 591,685.60**	**243,094.96**

[*]All values are considered as Present Values.

of the consumers remained at 1.5%, while the total urban water consumption was annually reduced by 1%. Undoubtedly, this reduction resulted not only by the pressure reduction, but also by a Strict Water Pricing Policy (increased water rates, Inclining block rates) and an Aggressive Public Awareness Campaign, both adopted by EYATH. As a result, the water consumption was annually decreased by 1% instead of the 1% annual increase expected. This means that since 2000, EYATH annually sold $1,360,000\,m^3$ less water ($9,520,000\,m^3$ for the 7-years period), than it would have sold, if no water saving measures were taken. These water savings must be added to the water savings ($7,224,668\,m^3$) resulting from the pipe break incidents prevented in the same period. Thus, the environmental importance of the entire project is strongly justified, as the total water savings since 2000 reached $16,744,668\,m^3$.

Economical aspect

The next step was to check the feasibility of the project through its cost-benefit analysis.

Costs

There were direct and indirect costs related to the project. Regarding the *direct costs*: a) the PRVs cost 54,514 €, while their annual operation/repair cost was 10,000 €; b) the technical consultant fee was 1,003,670 € (plus 50,000 € annual fee for its supervising services); c) the Public Awareness Campaign cost was 126,000 € for the year 2000 and 50,000 € for each year after. Regarding the *indirect costs* (lost revenues): since 2000, EYATH annually sold $1,360,000\,m^3$ less water ($9,520,000\,m^3$ till 2007), than it would have sold, if no measures were taken. Considering a mean water price of $0.60\,€/m^3$, the lost revenues were estimated to be 5,712,000 €. So, the total cost of the project for the 7-years period (2000–2006) was 7,556,184 €.

Benefits

Regarding the *benefits* related to the project: a) according to EYATH records, each break repair cost is 773 € (mean value-social cost not included). Thus, for the 5,324 breaks

prevented, EYATH saved 4,115,452 €; b) since 2000, as the water savings due to the pipe breaks prevented were $7,224,668\,m^3$, considering the relative water supply/treatment costs ($0.22\,€/m^3$), EYATH saved 1,589,427 €; c) since 2000, as EYATH annually sold $1,360,000\,m^3$ less water ($9,520,000\,m^3$ till 2007), than it should have sold, if no measures were taken, considering the abovementioned water supply/treatment costs, EYATH saved 2,094,400 €. So, the total benefit of the project for the 7-years period (2000–2006) was 7,799,279 €.

Cost-benefit analysis

The Cost-Benefit Analysis conducted (Figure 3 and Table 3) proves that the project is feasible (cost effective). Actually it has a less than 7-years Payback or Return of Investment period (time needed to balance the present values of benefits and costs). This period is reduced in 3.5 years if the social cost related to a pipe break (two times the actual break repair cost), is additionally considered. Finally, there is the immeasurable environmental profit for EYATH along with the fact that it will be able to postpone the search for additional water supplies and the huge related cost.

CONCLUSIONS – SUGGESTIONS

When a Water Utility manager is called to decide whether a proposed project, aiming to upgrade the network's performance level, will have the desired cost-effective results, he is usually forced to trust the project's ex-ante evaluation, based on assumptions rather than on actual facts. This is why he usually hesitates, having second thoughts. The project's ex-post evaluation is the only way to judge whether the initial decision regarding its approval was a good or a bad one. Ex-ante evaluation is what is available; ongoing evaluation is a failure-correcting process; ex-post evaluation is what is needed. But who can fast-forward the time? Experience resulting from upgrading projects implemented in networks of similar characteristics can be used as the most-desired time machine. The present paper shares such an experience resulting from the ex-post evaluation of a project that EYATH implemented in its water distribution network.

The Cost-Benefit Analysis of the network upgrading project presented here proved that this kind of project can be not only lifesaving but also feasible and cost-effective.

The suggestions to EYATH for an effective "confrontation" of water losses and their impacts are distinguished in two types regarding: a) the prevention of water losses and; b) their reduction or the minimization of their impacts. The pressure management project based on the installation of PRVs was the first step to control the water losses. This project should be regularly updated following the continuously changing needs of the distribution network.

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