Pipe replacement by age only, how misleading could it be?

M. A. Pardo and J. Valdes-Abellan

ABSTRACT

Traditional methods for prioritizing the renewal of water are based on heuristic models, such as the number of breaks per length, rule-of-thumb, and records held by the water utility companies. Efficient management of water distribution networks involves factoring in water and energy losses as the key criteria for planning pipe renewal. Prioritizing the replacement of a pipe according to the highest value of unit headloss due to ageing does not consider the impact on water and energy consumption for the whole network. Thus, this paper proposes a methodology to prioritize pipe replacement according to water and energy savings per monetary unit invested – economic prioritization. This renewal plan shows different results if comparing with replacing pipelines with regard to age and it requires calculating water and energy audits of the water distribution networks. Moreover, the required time to recover the investment performed needs to be calculated. The methodology proposed in this work is compared with the unit headloss criterion used in a real water-pressurized network. The results demonstrate that using the unit headloss criterion neither water, energy nor the investment is optimized. Significant water and energy savings are not fully exploited.

Key words | economic prioritization, energy efficiency, leakage, pipe replacement, water efficiency

M. A. Pardo (corresponding author)
J. Valdes-Abellan
Department of Civil Engineering,
University of Alicante,
Alicante,
Spain
E-mail: *mpardo@ua.es*

NOTATION

B_i (EUR)	Operation cost before pipe replacement
B_i^* (EUR)	Operation cost after i-pipe replacement
$C_{E,i}$ ($m^{3-\alpha}/s$)	Emitter coefficient at node i.
C_{ENV} (EUR/m^3)	Environmental cost of water
C_F (EUR)	Fixed costs of operation and maintenance
C_M (EUR)	Average break repair cost
$C_{tp}^{tot}(t)$ (EUR)	Present value of the total cost in the zero-action performed
$C_{tp\,i}^{tot}(t)$ (EUR)	Present value of the total cost in the decision of renovation of pipe i
C_W (EUR/m^3)	Cost of water
C_{WE} (EUR/kWh)	Cost of the energy
C_{p-i} (EUR)	Pipe costs
C_{inst-i} (EUR)	Installation costs
C_{ind} (EUR)	Indirect costs
C_{Si} (EUR)	Social costs
C_{Oi} (EUR)	Opportunity costs
I_i (EUR)	Investment performed
J (m/km)	Unit headloss of a pipe
K_f ($m^{3-\alpha}/s$)	Global value of the emitters
L_{pi} (m)	Weighted length of the node i
L_{pi+1} (m)	Weighted length of the pipe $i+1$
L_{pi}^* (m)	Weighted length of the node i after the renovation of a pipe
L_{pi+1}^*(m)	Weighted length of the node $i+1$ after the renovation of a pipe
L_T (m)	Total length of the network
m (-)	Number of pipes of the network
n (-)	Number of demand nodes of the network
P_{i-ser} (m.w.c.)	Minimum service pressure required for supplied demand

doi: 10.2166/ws.2018.131

$q_{li}(t)$ (m^3/s)	Leakage flow rate at node i at time t
S_i (EUR)	Economic savings obtained by the reduction of the leaks after renovation of pipe i
T_i (months)	Payback period
$V_{inj}(t)$ (m^3/s)	Total volume injected for the simulation period
α (-)	Emitter exponent
γ (N/m^3)	Specific weight of water
γ_{pi} (-)	Weighted leakage factor
$\Delta H_i(t)$ (m.w.c.)	Pressure variation through the leak at node i

INTRODUCTION

The US Environmental Protection Agency declared the nation's drinking water utilities need in infrastructure investments to be $334.8 billion (EPA 2013) over the next 20 years. England and Wales where water companies invested GBP 4.9 billion in 2014–15 (OFWAT 2018) are also declaring high needs and investments in water pressurized networks. So, pipe replacement has become an important challenge for utility managers, who must ensure safe water quality and structural performance with the minimization of the resources consumed.

Traditionally, decision-making alternatives for the rehabilitation of water distribution networks (WDN) have been based on indices such as the number of breaks per pipe (Hong *et al.* 2006) and the evolution of breakage rate with time (Alvisi & Franchini 2010). Some other approaches consider the unitary headloss related to pipe ageing (Kleiner *et al.* 2001), the minimization of the investment calculating the optimal pipe renovation period (Shamir & Howard 1979), or the minimization of the total cost of pipe replacement cycles to infinity (Kleiner *et al.* 2001). As this has been one of the hottest topics in the water industry, several decision support tools to obtain pipe replacement scheduling have been developed based on genetic algorithms (Alvisi & Franchini 2006) or on performance indicators (Pinto *et al.* 2017). Without any doubt, management of water losses (Marques & Monteiro 2003) have become one of the key goals for decision makers and practitioners due to scheduling pipe replacement in predetermined budget constraints (Alvisi & Franchini 2009).

The objective of this work is neither to find the most appropriate model to simulate water leakage nor to calibrate leakage model parameters, but to propose a methodology to prioritize pipe replacement in water pressurized networks. The criterion of grouping the pipelines eligible for obtaining the economic prioritization scheme is a specific problem for utility managers and the more homogeneous the District Metering Area (DMA) is, the better the results that are expected.

With these limitations, an economic prioritization is proposed for minimizing the period of time required to recoup the funds invested (payback period). This study considers direct costs as the cost of purchasing and installing the pipe (e.g., excavation, repaving, etc.) and also as the cost of the water and energy savings (calculated using the energy audit; Cabrera *et al.* 2010), indirect costs, environmental costs, social costs and opportunity costs (Rogers *et al.* 2002). Social costs are taxes proposed to compensate for the inconveniences created to people by public works and environmental costs are taxes destined to minimize the impact on the environment derived from the abstraction of water. Finally, the opportunity costs are the money savings derived from sharing some costs with other utilities (i.e. machinery, staff, tools, etc.).

The novelty of this methodology deals with the comparison between the current state of WDN (taking into account the rates of leakage obtained with the use of the water audit; IWA 2000) and those obtained after the renewal of each of the m pipes which are part of the network (formulating the problem as a discrete optimization problem). The assessment of water and energy savings is based on hydraulic models to calculate the response of each pipe replacement, and the pipe with the lowest payback periods should be the first selected for replacement. The lowest payback period is obtained for the pipe with the lowest ratio between investments and money savings. It is also pinpointed that pipelines with the largest water and energy savings are not necessarily the first selected for replacement according to this criterion.

The manuscript is organized as follows. The first subsection in 'Materials and methods' shows the simulation of leakage in WDN while the second subsection shows the effect of every replacement with regard to water and energy consumption (described in Appendix A). The replacement criteria analysed in this paper are shown in the third subsection and the definition of a real DMA where this method has been used is described in the fourth subsection (and also in Appendix B). The results obtained in the case study are shown in the first and second subsections under 'Results and Discussion' and the effect of other costs apart from the direct costs are described in the following third subsection. The effect of performing a pressure-driven analysis in comparison with a demand-driven analysis is shown in Appendix C, a detailed step-by-step prioritization case is shown in Appendix D and a sensitivity analysis of the effect of the environmental, opportunity and social costs is presented in Appendix E. (Appendices A–E are available with the online version of this paper.)

MATERIALS AND METHODS

A calibrated hydraulic simulation model is required to calculate water and energy audits of the pressurized water network.

Simulation of the leaky network

This approach deals with the idea of adding an emitter – a device that models the flow through a nozzle – at each node of the network (Cobacho *et al.* 2015; Equation (1)) in order to consider water leakage as pressure-dependent on node demands:

$$q_{li}(t) = C_{E,i} \cdot [\Delta H_i(t)]^{\alpha} = K_f \cdot \gamma_{pi} \cdot [\Delta H_i(t)]^{\alpha} \quad (1)$$

where $q_{li}(t)$ (m^3/s) is the sum of the background and bursts leakage flow rate at node i, $C_{E,i}$ ($m^{3-\alpha}/s$) is the emitter coefficient, $\Delta H_i(t)$ (m) is the pressure variation through the leak at time t, and α (–) is the pressure exponent that models the characteristics of the pipe material. K_f ($m^{3-\alpha}/s$) is the global value which considers the leakage level and γ_{pi} (–) is a weighted leakage factor which represents the importance of each node with regard to leakage. This equation produces good results if the pressure exponent is in the range 0.5–2.95 (Van Zyl & Malde 2017) and if the pressure in the DMA is above the threshold pressure value (normal functioning with no pressure deficient conditions). In case of pressure deficit, pressure-driven simulation should be considered.

Since the location of background leakages is not known, it can be assumed that leakage is uniformly distributed along every pipeline of the WDN. Based on common modelling assumptions, water leakage at nodes is equal to the water losses produced in the half of all pipes connected to it (Equation (2)). Let us assume that the leakage factor γ_{pi} can just be the pipe length:

$$\gamma_{pi} = \frac{\sum (\gamma_j/2)}{\gamma_T} = \frac{(L_1/2) + (L_2/2) + \ldots + (L_j/2)}{L_T} \quad (2)$$

where L_j (m) are the lengths of pipes connected to each node and L_T (m) is the sum of all pipe lengths of the network. So there is a different factor for each node and these must sum to one. If leakage in the DMA is not homogeneous, these γ_{pi} coefficients may adopt various values (such as the number of repairs per pipe length) with the restriction that the n coefficients must sum to one.

Simulation of the *m* replacement cases

Given a network with m pipelines eligible for replacement, m scenarios may arise for analysing water and energy consumption. The replacement of each pipeline assumes it to be a leak-free pipeline. It means that the burn–in phase in the bathtub curve of the life cycle of a buried pipe (Kleiner & Rajani 2001) is over and there is no break after the replacement. As a consequence of the replacement, new weighted leakage factors (Equation (2)) are expected.

For instance, if the jth pipe has been selected for replacement, the leakage factor γ_{pi} is now calculated as follows (Equation (3)):

$$\gamma_{pi} = \frac{\sum (\gamma_j/2)}{\gamma_T} = \frac{0 + (L_{j+1}/2) + (L_{j+2}/2)}{L_T} \quad (3)$$

Each one of the possible scenarios has new values in some of the n (number of nodes) weighted leakage factors. These new values involve changes in some of the n emitters (there is no change of the K_f value; Equation (1)) and new levels of water leakage. Moreover, pipe roughness is a property that may change as pipes age and this variation can have a large effect on the WDN headlosses. In order to arrange this effect, the pipe roughness of the new pipe has lower values than the aged pipe. The changes performed on leakage parameters (at nodal level) and in the pipe roughness (at pipe level) involve a different flow distribution through the system and consequently, new pressure levels at every node of the network. Moreover, the calculation of leakage in the new *m* scenarios (using water and energy audits as described in Appendix A and comparing the new results with the zero-case scenario) reveals the joint effect of these new parameters and of the hydraulic status.

Pipe renewal criteria

Unit headloss prioritization criterion

The unit headloss represents the energy headlosses per length of the pipe, quantified in metres of water column dissipated by friction per kilometre of pipeline (m/km). It depends on flow and on the hydraulic resistance of the pipe. Pipe hydraulic resistance in WDNs is computed for fully turbulent conditions (transitional and laminar flow are only in theory) due to the presence of connections, changes in pipe directions and variation of water demands. So, this method consists in selecting the pipe with the highest daily average unit headloss among the *m* potential candidates as the first pipeline to be replaced. The key advantage of this criterion is its simplicity and it is a commonly adopted approach by water utilities which plan rehabilitation mainly based on pipe age (because of the assumed higher internal roughness), but, in contrast, it does not consider the impact of a single-pipe replacement on the hydraulic behaviour of the whole network.

Economic prioritization criterion

The economic prioritization criterion involves calculating the water and energy audits for each of the *m* cases and comparing with the zero case (current state of the network). The indicator that should be used for obtaining the prioritization scheme is the payback period.

Moreover, this investment has to be paid at the present time while water and energy savings are periodically obtained. In order to be able to compare, all costs should be expressed in monetary units at the present time with the use of the equivalent continuous discount rate, *r*.

The operation costs that the utility should face in a non-replacement scenario (the *laissez faire* option or the cost of doing nothing) from the present time – t_p – to the time *t* can be expressed as Equation (4):

$$C_{tp}^{tot}(t) = \int_{tp}^{t} (C_F + C_M + (C_W + C_{ENV})V_{inj} + C_{WE}\,E_{input}) .e^{-rt}dt = \int_{tp}^{t} B_i\,e^{-rt}dt \quad (4)$$

where C_F (EUR) is the fixed costs with regard to operation and maintenance of the network, C_M (EUR) is the average break repair cost (a value that can be calculated as the repair cost of a single break multiplied by the number of breaks that appear from present time to time *t*), C_W (EUR/m^3) is the cost of water (this value is a sum of the fixed cost depending on the utility structure and the variable costs of collection, treatment and distribution, excluding energy costs), C_{ENV} (EUR/m^3) is the environmental cost of water, highly variable, from 0.84 to 0 EUR/m^3 in Denmark and Spain respectively (EPO 2010) and C_{WE} (EUR/kWh) is the cost of the energy consumed, sum of the variable costs of energy in the collection, treatment and distribution stages of the urban water cycle. Finally, B_i (EUR) is the operation costs of the water network for the period t_p–t.

Analogous to the previous equation, the present value of the operation costs that the utility should face from now (replacement of the *i*th pipe) to *t* is calculated as Equation (5):

$$C_{tp\,i}^{tot}(t) = ((C_{p-i} + C_{inst-i}) + C_{ind-i} - C_{Oi} + C_{Si}) - \int_{tp}^{t} \left(C_F + C_M + (C_W + C_{ENV})V_{inj}^{*} + C_{WE}\,E_{input}^{*}\right) .e^{-rt}dt = I_i - \int_{tp}^{t} B_i^{*}.e^{-rt}dt \quad (5)$$

where $C_{p\text{-}i}$ (EUR) is the pipe cost itself, $C_{inst\text{-}i}$ (EUR) is the pipe installation costs (these grouped together represent the direct pipe replacement costs). The indirect costs ($C_{ind\text{-}i}$; EUR) of pipe replacement are administration, personnel, security costs, etc. Social costs (C_{Si}; EUR) are proposed to compensate for the inconveniences caused to people by public works. The opportunity costs (C_{Oi}; EUR) are associated with the savings derived from renewing the pipe while performing other utility or road works which are more urgent and as a consequence, some costs are shared (i.e. machinery, staff, tools, etc.) and the savings can even reach the total cost of the installation if other works are in charge of digging and replacing the pavement. I_i (EUR) represents the investment performed in pipe i and B_i* (EUR) is the new operation cost encompassing the energy and water consumed after the replacement of pipe i.

Finally, the equation resulting when comparing the operation costs of the *laissez faire* option with the replacement of pipe i is Equation (6):

$$C_{tp\,i}^{tot}(t) - C_{tp}^{tot}(t) = I_i + \int_{tp}^{t} (B_i^* - B_i).e^{-rt}dt = I_i - \int_{tp}^{t} S_i.e^{-rt}dt \tag{6}$$

where S_i (EUR) are the economic savings obtained by the renovation (B_i* has a lower value than B_i, as the replacement involves water and energy savings). Note that the fixed costs (C_F; EUR) are equal for each of the cases compared and the maintenance costs are considered to have similar values in homogeneous DMAs and due to this are irrelevant for this study. Equating to zero the derivative of Equation (6), the payback period of the investment (Equation (7)) is calculated:

$$T_i = \frac{-1}{r} \cdot \ln\left(1 - \frac{I_i \cdot r}{S_i}\right) \tag{7}$$

where T_i (months) is the payback period, which is the value to minimize as lower values involve higher water and energy savings per monetary unit invested.

Numerical example

To illustrate the proposed methodology, a numerical example is presented. Figure 1 shows a DMA in a western Mediterranean city in Spain. The pipe material is ductile iron and the pipe roughness for the aged pipes is 0.2 mm, these figures being of the same order of magnitude as those considered by Christensen (2009), and the pipe roughness of the newly installed pipe is equal to 0.1 mm (McGovern 2011), a usual value in WDN. The emitter exponent is equal to 1. The utility facilitates the leakage rate of

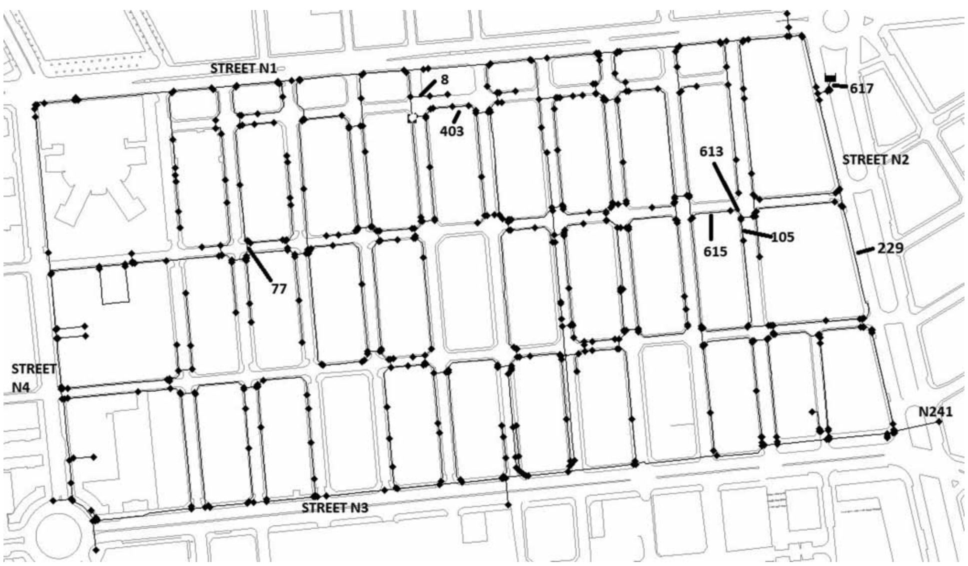

Figure 1 | General layout of the network.

the network (10%) and the minimum service pressure required is 20 m.w.c.

The cost of water and energy is 1.89 EUR/m^3 (INE 2016) and 0.084 EUR/kWh (MINETAD 2017) respectively. The renewal cost of pipes considered in the study is 1.096 EUR/m/mm ($C_{p-i} + C_{inst-i}$), a real value obtained by a water utility which operates in Spain (this cost allows the practitioners to get the cost of every pipeline in the water network as the cost is proportioned considering the pipe length in m and the pipe diameter in mm).

The indirect cost will be considered as 6% of the direct costs (a value proportioned by the water utility). The social, the opportunity and the environmental costs are zero for the DMA analysed (although an analysis of the specific importance of each of them is calculated later). Finally, the equivalent continuous discount rate is $r = 2\%$.

As this methodology is very time-consuming (the values of energy savings at every time-step period vary, daily sums of energy/water saved have been calculated), every hydraulic simulation of the 617 scenarios (with their water and energy audits) have been calculated using the Matlab® code to assist with the EPAnet toolkit (Rossman 2000).

RESULTS AND DISCUSSION

Prioritization results in the unit headlosses methodology

Results are depicted in Table 1 where the four pipes with the highest average values of the unit headlosses are displayed. According to these, the renovation order is pipe 105, 403, 613 and 615. This methodology does not consider the global energy and water savings produced as a consequence of a pipe renewal so there is no additional information about the impact of the renewal action.

Table 1 | Prioritization results for the unit headloss criterion (a) and the economic criterion (b)

(a) Unit headlosses prioritization				**(b) Economic prioritization**			
	ID	**A[a]**	**B[a]**		**ID**	**A[a]**	**B[a]**
1st	105	0.806	132.79	1st	8	0.094	107.90
2nd	403	0.574	115.99	2nd	403	0.574	115.99
3rd	613	0.570	132.41	3rd	615	0.549	126.21
4th	615	0.549	126.21	4th	77	0.038	127.05

[a]A (m/km); B (months).

Economic criteria prioritization results

The priority obtained is different compared with the unit headlosses methodology. The results indicate that the new order is now pipe 8, 403, 615 and 77 (Table 1).

If the unit headloss methodology is the criterion selected for replacement, pipe 105 (best result) involves daily savings of 157.10 litres and 0.024 kWh, while pipe 8 replacement would save 136.14 l/day and 0.021 kWh/day. But the investment performed with pipe 105 replacement is equal to 1,068.54 EUR (as the length of the pipe is 18.2 m and its current diameter is 50.53 mm) while the investment of pipe 8 replacement is equal to 767.67 EUR (length 16.57 m, diameter 39.87 mm) and considering these numbers, pipe 8 replacement produces higher savings (1 EUR saves 64.78 litres and 0.01 kwh per year) than pipe 105 replacement (in which 1 EUR saves 53.75 litres and 0.008 kWh).

Table 1 collects the payback period (in months). As can be concluded from those results, when high hydraulic efficiency scenarios are analysed, economic investment is slowly recovered because the energy and water savings are low (as in the current case study); in contrast, when water networks present low levels of water losses, pipe replacement planning is very interesting from an economic point of view. Some pipe replacements considered in the calculations show payback periods equal to infinity (55 pipelines out of 617); in other words, the investment is never recouped from the low savings produced.

Influence of the environmental, social and opportunity costs

In order to consider the influence of the environmental cost on the payback period of the investment, some values (EUR/m^3) are proposed (0.05; 0.1; 0.15; 0.2). These figures are low compared with the aforementioned values of Denmark (EPO 2010). The effect of the environmental costs brings little surprise, and the higher environmental costs result in the lowest payback period (Tables 2 and 3).

Table 2 | Payback period (in months) for replacement without considering additional costs

	ID	Pipe costs (€/m)	Volume savings (m^3/day)	Energy savings (kWh/day)	I_i (€)	S_i (€)	Payback period (months)
1st	8	43.70	0.14	0.02	767.51	7.77	107.88
2nd	403	46.97	0.12	0.0	705.90	6.70	115.94
3rd	615	52.45	0.30	0.0	1,927.87	16.95	126.11
-	229	209.03	0.70	0.1	17,490.80	39.64	797.86

Table 3 | Effect of the environmental costs on the payback period (in months)

Env. costs (€/m^3)			0.05	0.1	0.15	0.2	0.05	0.1	0.15	0.2
	ID	I_i (€)	S_i (€)				Payback period (months)			
1st	8	767.51	7.977	8.182	8.39	8.59	104.86	102.01	99.31	96.74
2nd	403	705.90	6.871	7.047	7.22	7.40	112.68	109.59	106.67	103.90
3rd	615	1,927.87	17.395	17.840	18.29	18.73	122.53	119.15	115.95	112.91
-	229	17,490.80	40.678	41.720	42.76	43.80	756.61	719.88	686.91	657.11

The social cost values considered should be different with regard to every street in the DMA studied. Here, streets N1, N2, N3 and N4 (Figure 1; 109 pipes whose length is 2,224 m, 20.97% of the total network) are considered to have social costs equal to 0.109, 0.219 and 0.329 EUR/m/mm (10%, 20% and 30% of 1.096 EUR/m/mm, the sum of the pipe and installation costs; Cobacho *et al.* 2009) while the rest of the network has social costs equal to 0 EUR/m/mm. These costs influence the payback periods, increasing the payback period for the pipelines located in these streets (Table 4). The prioritization scheme shown in Table 1 is not modified as the pipelines selected for replacement are not installed in these streets.

Finally, the opportunity costs considered can be a reduction of 10%, 20% and up to 30% of the pipe replacement cost (Cobacho *et al.* 2009) – in other words, a reduction of the pipe cost of 0.109, 0.219 and 0.329 EUR/m/mm for every pipeline considered. The results indicate that the payback period of the *i*th pipe replacement decreases if the opportunity arises. As may be observed in Table 5, the payback period for pipe 8 is equal to 107.90 months and if opportunity costs are larger than 0.0695 (pipe 403) and 0.1446 EUR/mm/m (pipe 615), the payback period is lower than this value (107.90) and the opportunity must be seized. The calculation of the threshold value (0.0695 EUR/mm/m) for pipe 403 is described in detail in Appendix E.

Table 4 | Effect of the social costs on the payback period (in months)

S. costs (€/m/mm)			0.1096	0.2192	0.3288	0.1096	0.2192	0.3288
	ID	S_i (€)	I_i (€)			Payback period (months)		
1st	8	7.773	767.51			107.88		
2nd	403	6.696	705.90			115.94		
3rd	615	16.949	1,927.87			126.11		
-	229	39.637	19,239.88	20,985.77	22,738.05	993.31	1,284.38	1,875.50

Table 5 | Effect of the opportunity costs on the payback period (in months)

Opp. costs (€/m/mm)			0.1096	0.2192	0.3288	0.1096	0.2192	0.3288
	ID	S_i (€)	I_i (€)			Payback period (months)		
1st	8	7.773	690.76	614.01	537.26	96.18	84.70	73.43
2nd	403	6.696	635.31	564.72	494.13	103.29	90.89	78.75
3rd	615	16.949	1,735.08	1,542.29	1,349.51	112.24	98.68	85.42
-	229	39.637	15,741.72	13,992.64	12,243.56	650.68	532.58	433.95

CONCLUSIONS

Water utility managers have considered unit headloss methodology as one of the criteria for pipe replacement. However, this study demonstrates that following this criterion neither water and energy nor the financial investment is optimized and significant savings are not fully exploited.

The methodology proposed to prioritize the replacement plan is based on economic factors and involves maximizing the energy and water savings per monetary unit invested. In each of the *m* scenarios considered, the diameter of the aged pipe has been maintained and a new roughness value has been considered to model its hydraulic response. Energy and water audits are carried out in leaky networks to calculate the savings obtained as a consequence of the replacement.

Results have demonstrated that opportunity costs do not necessarily involve large savings and the prioritization scheme is not always modified. It has been proved that a threshold value for taking or rejecting the opportunity exists and it can now be calculated. On the other hand, the existence of environmental costs of water involve lower payback periods, and social costs are considered to make the simulation more realistic, as in every DMA, water managers cannot decide when to carry out digging and repaving works without considering the social problems.

Although leakage reduction is the main positive effect of pipe replacement, it implicitly reduces the risk of bursts and service interruption (considered in the social cost) and it also increases the hydraulic capacity of the WDN. Scenarios with low hydraulic efficiency (high leakage flowrate) involve quick recovery of the economic investment because of the high energy and water savings.

This methodology should be used for homogeneous groups of pipelines (all of them with the same age). The more homogeneous the DMA is, the better the results that are obtained. In other words, it cannot be used for comparing pipelines at different ages. Finally, as pipelines in the DMA are considered to have the same age, the number of breaks and their repair costs (maintenance costs) can be considered as fixed costs, and they can also be considered irrelevant for this study.

ACKNOWLEDGEMENTS

This work was supported by the research project 'GESAEN' through the 2016 call of the Vicerrectorado de Investigación, Desarrollo e Innovación de la Universidad de Alicante GRE-16-08. The translation of this paper has been funded by the Escuela Politécnica Superior, University of Alicante.

REFERENCES

Alvisi, S. & Franchini, M. 2006 Near-optimal rehabilitation scheduling of water distribution systems based on a multi-objective genetic algorithm, *Civil Engineering and Environmental System Journal* **23** (3), 143–160.

Alvisi, S. & Franchini, M. 2009 Multiobjective optimization of rehabilitation and leakage detection scheduling in water distribution systems. *Journal of Water Resources Planning and Management* **135** (6), 426–439.

Alvisi, S. & Franchini, M. 2010 Comparative analysis of two probabilistic pipe breakage models applied to a real water distribution system. *Civil Engineering and Environmental System Journal* **27** (1), 1–22.

Cabrera, E., Pardo, M. A., Cobacho, R. & Cabrera Jr, E. 2010 Energy audit of water networks. *Journal of*

Water Resources Planning and Management **136** (6), 669–677.

Christensen, R. T. 2009 *Age Effects on Iron-Based Pipes in Water Distribution Systems*. PhD thesis. Civil and Environmental Engineering, Utah State University, UT, USA. https://digitalcommons.usu.edu/etd/505 (accessed 24 May 2018).

Cobacho, R., Cabrera, E., Cabrera Jr, E. & Pardo, M. A. 2009 Effect of water costs on the optimal renovation period of pipes. In: *Strategic Asset Management of Water Supply and Wastewater Infrastructures* (H. Alegre & M. d. C. Almeida, eds), IWA Publishing, London, UK, pp. 231–245.

Cobacho, R., Arregui, F., Soriano, J. & Cabrera Jr, E. 2015 Including leakage in network models: an application to calibrate leak valves in EPANET. *Journal of Water Supply: Research and Technology – Aqua* **64** (2), 130–138.

EPA 2013 *Drinking Water Infrastructure Needs Survey and Assessment: Fifth Report to Congress*. EPA 816-R-13-006, US EPA, Office of Water, Washington, DC, USA. https://www.epa.gov/sites/production/files/2015-07/documents/epa816r13006.pdf (accessed 24 May 2018).

Eurostat Press Office (EPO) 2010 *Facts and Figures on the Environment: From Environmental Taxes to Water Resources*. Eurostat Press Office, Luxembourg.

Hong, H. P., Allouche, E. N. & Trivedi, M. 2006 Optimal scheduling of replacement and rehabilitation of water distribution systems. *Journal of Infrastructure Systems* **12** (3), 184–191.

INE 2016 Encuesta sobre el suministro y Saneamiento del Agua, Año 2014. Press release, Instituto nacional de estadística, Madrid, Spain. http://www.ine.es/prensa/np992.pdf (accessed 24 May 2018).

IWA 2000 *Losses from Water Supply Systems: Standard Terminology and Recommended Performance Measures*. International Water Association Task Force on Water Losses, IWA, London, UK.

Kleiner, Y. & Rajani, B. 2001 Comprehensive review of structural deterioration of water mains: statistical methods. *Urban Water* **3** (3), 131–150.

Kleiner, Y., Adams, B. J. & Rogers, J. S. 2001 Water distribution network renewal planning. *Journal of Computing in Civil Engineering* **15** (1), 15–26.

Marques, R. & Monteiro, A. 2003 Application of performance indicators to control losses – results from the Portuguese water sector. *Water Science and Technology: Water Supply* **3** (1–2), 127–133.

McGovern, J. 2011 *Technical Note: Friction Factor Diagrams for Pipe Flow*. Dublin Institute of Technology, Dublin, Ireland. https://arrow.dit.ie/engschmecart/28/ (accessed 24 May 2018).

Minetad 2017 *Precio Neto de la Electricidad Para uso Doméstico Y uso Industrial*. Ministerio de Energía, Turismo y Agenda Digital (in Spanish). http://www.minetad.gob.es/es-ES/IndicadoresyEstadisticas/DatosEstadisticos/IV.%20Energ%C3%ADa%20y%20emisiones/IV_12.pdf (accessed 24 May 2018).

OFWAT 2018 *Annual Performance Report*. https://www.ofwat.gov.uk/regulated-companies/company-obligations/performance/companies-performance-2014-15/financial/ (accessed 24 May 2018).

Pinto, F. S., Costa, A. S., Figueira, J. R. & Marques, R. C. 2017 The quality of service: an overall performance assessment for water utilities. *OMEGA*, *The International Journal of Management Science* **69** (1), 115–125.

Rogers, P., de Silva, R. & Bhatia, R. 2002 Water is an economic good: how to use prices to promote equity, efficiency, and sustainability. *Water Policy* **4** (1), 1–17.

Rossman, L. A. 2000 *EPANET 2: User's Manual*. US Environmental Protection Agency, Cincinnati, OH, USA.

Shamir, U. & Howard, C. D. D. 1979 An analytic approach to scheduling pipe replacement. *Journal of American Water Works Association* **71** (5), 248–258.

Van Zyl, J. E. & Malde, R. 2017 Evaluating the pressure-leakage behaviour of leaks in water pipes. *Journal of Water Supply Research and Technology – AQUA* **66** (5), 287–299.

First received 8 March 2018; accepted in revised form 26 June 2018. Available online 11 July 2018