Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 89 (2014) 29 – 36
Procedia Engineering
www.elsevier.com/locate/procedia

16th Conference on Water Distribution System Analysis, WDSA 2014

BBLAWN: a Combined Use of Best Management Practices and an Optimization Model Based on a Pseudo-Genetic Algorithm

P. L. Iglesias-Rey[a]*, F. J. Martínez-Solano[a], D. Mora Meliá[b], P. D. Martínez-Solano[c]
[a]*Dep. Ingeniería Hidráulica y Medio Ambiente. Universitat Politècnica de València. Camino de Vera s/n. 46022 Valencia (Spain).*
[b]*Dep. de Ingeniería y Gestión de la Construcción. Facultad de Ingeniería. Universidad de Talca. Camino de los Niches km 1. Curicó (Chile).*
[c]*Empresa Municipal de Aguas y Saneamiento de Murcia, S.A. C/Doctor Alonso Espejo, n° 8. 30007 Murcia (Spain).*

Abstract

The paper presents a solution to the problem of the Battle of Background Leakage Assessment for Water Networks (BBLAWN) using a methodology that combines the use of Best Management Practices (BMPs) and an optimization model based on a Pseudo-Genetic Algorithm (PGA) as described in [1]. In a first stage, an analysis of marginal costs of pipes whose replacement would be potentially recommended was performed. Next, a network topological analysis to study the pipes that could potentially be closed in order to facilitate pressure control was done. Furthermore, a methodology for studying branched areas was also developed, determining possible location for pressure reducing valves (PRV). A significant reduction in the number of decision variables was obtained and a specific optimization model was developed.

Peer-review under responsibility of the Organizing Committee of WDSA 2014
Keywords: Background Leakage; Pressure Reducing Valves; Optimization; Genetic Algorithms

1. Introduction

In this work, it is presented a methodology for reducing water losses due to background leakages combined with a pumping scheduling optimization. Some previous works [1,3] show how heuristic optimization methods can be a good solution to optimize a water distribution network. Also, throughout the different editions of the Battle of Water Networks [3] has been shown how the use of Best Management Practices (BMPs) contributes to properly solve

---

* Corresponding author. Tel.: +34 96 387 7610; fax: +34 96 387 7618.
E-mail address: piglesia@upv.es

Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.156

optimization problems. Moreover, sometimes the use of these BMPs can get as suitable solutions as those obtained by complex optimization models running on supercomputers. For this reason, in this paper a methodology based on the combined use of a Pseudo-Genetic optimization model and some BMPs is presented. Some BMPs used in this methodology are related with sectorization and leakage control y water distribution networks.

For purposes network hydraulic analysis the EPANET model [2] has been used. So the work has been structured in three different parts. First pretreatment of existing information is performed. Subsequently, the assumptions and adjustments made in the initial model to be further analyzed and optimized with EPANET are discussed. From the initial network, a general optimization model is developed. This model optimizes all network elements: pipes replacement, pumping scheduling, setting of the control valves and tanks sections increase. The general optimization model can be alternatively applied both to water mains and defined subareas (SAs). Systematic application of this optimization model, a continuous update of the District Metering Areas (DMAs) and SAs of the network and the application of a manual fine adjustment, leads to the proposed solution.

2. Initial data pre-processing

Before applying the proposed methodology, some previous studies on the initial information available have been made. Thus, after a first study, expanding the network tanks has not been considered. The high cost of expanding tanks do not seems to make up the potential energy savings that can be obtained. The two critical parameters in BBLAWN costs reduction are water leakage reduction and energy costs decreasing. For this reason, criteria to change pipes and pumps have been established according to cost analysis.

2.1. Pipe change criteria

The background leakage model used is based in the model for water losses proposed by Germanopuolos [4]. He defines the water leakage flow Q_f as

$$Q_f = \beta \cdot L \cdot p^{\alpha} \tag{1}$$

In the equation (1), L is the pipe length; p is the mean pressure; α and β are pipe characteristic model parameters. In this case the parameter α is 0.9 for all pipes and β is different depending the DMA considered. One of the main criteria for reducing losses in BBLAWN is changing the existing pipes with new pipes, reducing the value of β parameter. For this, a pipe cost analysis was performed. This analysis compares the cost savings in water leakages with the capital cost of a new pipe. This allows determining for each β value, the minimum pressure to change a pipe with a new one of the same diameter. Results of this analysis are shown in Fig.1. Applying the criteria of Fig. 1, a first pipe replacement was performed.

2.2. Pump change criteria

Facing an optimal pumping schedule, an analysis was done on the best number of pumps to be operated. From the pump power curves, it has been observed that the best situation for the energy consumption in a pumping station is to work with as few pumps as possible. Let *Q* the flow pumped by a pump. The power consumed by a pump when its flow is *Q* is given by equation (2):

$$\left.\begin{array}{r} H = H_{\max} - r\cdot Q^{c} \\ \eta = 4\eta_{\max}\left[\dfrac{Q}{Q_{\max}} - \left(\dfrac{Q}{Q_{\max}}\right)^{2}\right] \end{array}\right\} \Rightarrow \quad P = \frac{\gamma Q H}{\eta} = \frac{\gamma Q_{\max} H}{4\eta_{\max}\left(1 - \dfrac{Q}{Q_{\max}}\right)} \tag{2}$$

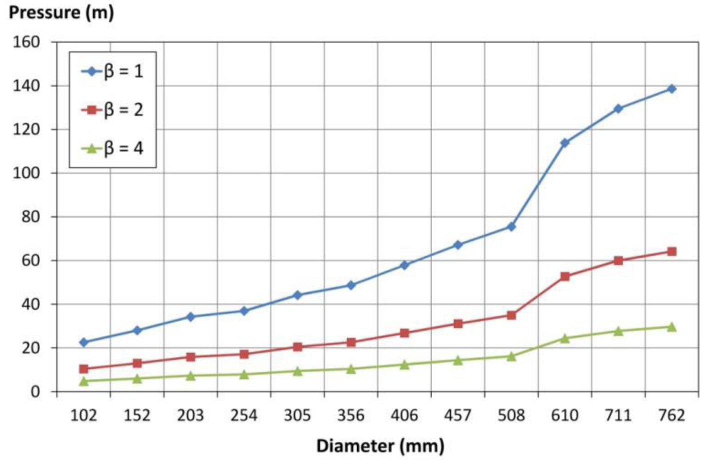

Fig. 1. Minimum pressure for pipe replacement.

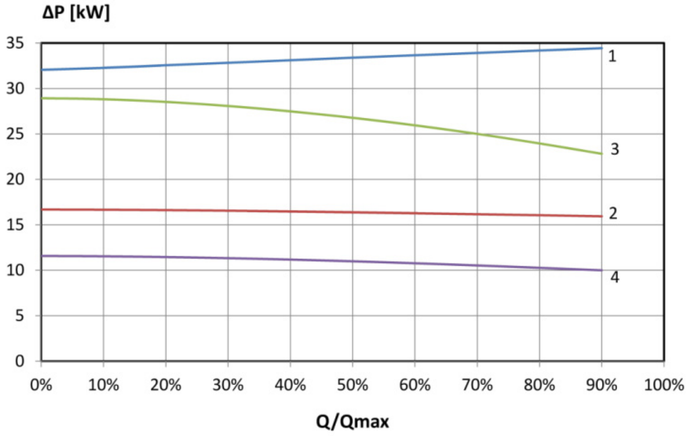

Fig. 2. Comparison between powers required to pump a flow with one or two pumps.

For the same flow Q, it is possible to use two pumps delivering half the flow each. In this case, Fig. 2 shows the comparison between the energy used by one pump, P(Q), and the power used by two pumps working in parallel, 2·P(Q/2). That is:

$$\Delta P = 2 \cdot P(Q/2) - P(Q) \tag{3}$$

As there was a possibility of changing pumps, a second analysis was done in order to find the point from which such a change could be profitable. Old pumps have a maximum efficiency of 70% meanwhile new ones reach the 80%. For the same usage and the same power, the saving in energy costs (ΔC) obtained by changing a pump is given by:

$$\Delta C = \frac{0.1}{0.8} C_E \tag{4}$$

So, if this saving is bigger than the cost of the new pump (C_P), the old pump will be substituted. From the reasoning above, the annual energy cost (C_E) that allows a reduction in the total cost by changing the pump has been calculated for each pump type. The results are shown in Table 1.

Table 1. Pump Minimum energy cost change criteria.

Pumping Station	Pumps	Curve Number	Pump annual cost C_P (€)	Energy cost C_E (€)
S1	PU1, PU2, PU3	1	4133	33 064
S2	PU6, PU7	2	3563	28 504
S3	PU4, PU5	3	4339	34 712
S4	PU10, PU11	2	3563	28 504
S5	PU8, PU9	4	3225	25 800

3. Background leakage model for pipes

As a hydraulic solver, EPANET engine was used for this network. EPANET allows considering leakages as pressure-dependent demands using emitters. However, there is a difference between this model and the model proposed by Germanopoulos [4], which is the suggested model. Germanopoulos proposes that the leakage through a pipe depends on the average pressure meanwhile the use of emitters in EPANET makes the leakage depend on the pressure at the end nodes of it:

$$Q_f = \beta \cdot L \cdot \left(\frac{p_1 + p_2}{2} \right)^{\alpha}$$
$$Q_f = \frac{\beta \cdot L}{2^{\alpha}} \cdot \left(p_1^{\alpha} + p_2^{\alpha} \right) \qquad (5)$$

After a mathematical comparison between these two models, the following approach was done in order to reduce the error arisen from the use of emitters in EPANET:

$$\left(p_1 + p_2 \right)^{\alpha} = 0.953 \cdot \left(p_1^{\alpha} + p_2^{\alpha} \right) \qquad (6)$$

However, there is still another problem with the leakage model. EPANET does not allow to allocate demands to pressure nodes (that is, to tank or reservoirs). This is another source of error, which was solved by creating fictitious nodes at the location of every tank. The connection between the tank and the new node was done with a dummy pipe of large diameter and Hazen-Williams coefficient, and small length. For the final evaluation of the model, the equation (1) will be used in order to reduce possible errors.

4. Optimization model

4.1. Objective function

The objective function of this problem has two main parts: costs and constraints. Costs include operational and capital costs. Environmental costs related to background leakage are considered operational costs together with energy costs. On the other hand, capital costs account for pipe and pump replacement, tank enlargement and control valve installation. Some constraints have been also considered: minimum pressure at junctions, emptying of tanks, and recurrence in tanks. Recurrence in tanks implies that at the end of simulation the volume at the tank must be at least the same that the volume at the beginning. Each restriction has been corrected with a Lagrangian penalty multiplier (β_i) to account for the different scale of the parameters.

From previous works [1,5] it was concluded that it is recommended to add a multiplier parameter $\beta_0 \cdot \delta_0$, which represents only the existence of some kind of penalty in the system. δ_0 is a binary variable that adopts value 1 if δ_1, δ_2 and δ_3 are not zero. If all constraints are accomplished, δ_0 takes a value of 0, while if any of the constraints are violated, then δ_0 takes a value of 1. β_0 takes a large value to separate this solution from solutions with no penalties.

Finally, the objective function shown in equation (7) was used:

$$\begin{aligned}&\left[\sum_{i=1}^{N_{pumps}}\left(C_{P,i}+52\sum_{j=1}^{N_{time}}\frac{\gamma H_{ij}Q_{ij}}{\eta_{ij}}\cdot C_{E,j}\right)+\sum_{i=1}^{N_{pipes}}\left(C_{P,i}\cdot L_i+52\cdot C_F\sum_{j=1}^{N_{time}}Q_{f,ij}\right)+\sum_{i=1}^{N_{\tan ks}}C_{T,i}+\sum_{i=1}^{N_{valves}}C_{V,i}\right]+\\&+\beta_0\delta_0+\beta_1\left[\sum_{i=1}^{N_{junc}}\sum_{j=1}^{N_{time}}\delta_{1,ij}\left(p_{\min,i}-p_{ij}\right)\right]+\beta_2\left[\sum_{i=1}^{N_{\tan ks}}\sum_{j=1}^{N_{time}}\delta_{2,ij}\left(z_{\min,i}-z_{ij}\right)\right]+\beta_3\left[\sum_{i=1}^{N_{\tan ks}}\delta_{3,i}\left(z_{i,0}-z_{i,N_D}\right)\right]\end{aligned} \tag{7}$$

4.2. Decision variables

Initially, the optimization problem has a large number of decision variables (DV). All pipes may be replace or duplicate. Besides, in order to reduce pressures in some areas of the network, some pipe can be closed. Tanks may be expanded. Pumps and valve V2 must be controlled by level at tanks. Finally, each pipe may potentially have a pressure-reducing valve (VRP) and these VRPs can be controlled along simulation time. The result is almost 74000 decision variables as summarizes in Table 2.

Table 2. DVs used in the optimization model.

Concept	Number of Elements	DVs / Element	DVs
Pipe Diameters	432	1 (Diameter)	432
Potential Pipe Closures	432	1 (Open / Close)	432
Extension of Tanks Capacity	7	1(Cross Section)	7
Pumps Control	11	3 (Start/stop level and initial status)	33
Valve V2	1	3 (Start/stop level and initial status)	3
Potential VRPs location	432	1 (Yes /No)	432
Time setting for VRPs	432	168 (No of time steps)	72576
Total			73915

5. Methodology

In order to reduce the number of decision variables and speed up the optimization model, the problem has been divided into three stages: pre-processing, optimization and post-processing. The pre-processing stage has been described above. After the pre-processing step, a new, modified model was obtained. This will constitute the basic network for the optimization process. After that, the network was divided into main pipes and subareas. They were optimized separately. Then, the new network will be post-processed to improve the solution through fine adjustments based on best management practices (BMPs). Fig. 3 shows a flow chart with the whole optimization process.

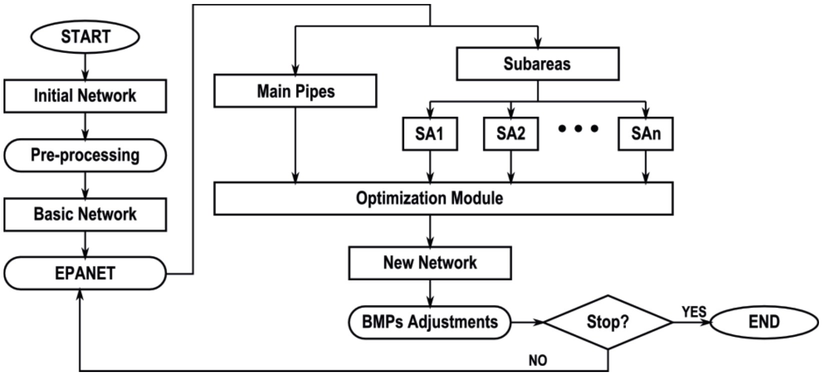

Fig. 3. Flow chart of the optimization process.

5.1. Network skeletonization and subareas (SA) definition

The basic network obtained after the pre-processing stage was studied to divide it into main transport network and district metering areas and subareas. Each subarea has been studied separately to select the critical nodes and to propose potential location of valves that control it. As a starting point, an initial analysis with EPANET was performed so an initial distribution of pressures and flow could be used. The model of every subarea was then optimized considering only pipe replacement and VRPs location and setting. The results (VRPs location and settings) were added to the main network. Then, the main network is optimized in order to perform a global optimization process, which minimizes the value of the objective function presented in equation (7). For the definition of subareas, the criterion is that branched networks were preferred. Therefore, some pipes have to remain closed in order to branch the subarea network. When a subarea can be supplied from several nodes, a descendent topographical line was preferred. After the study, 32 subareas were defined. Fig. 4 shows these subareas.

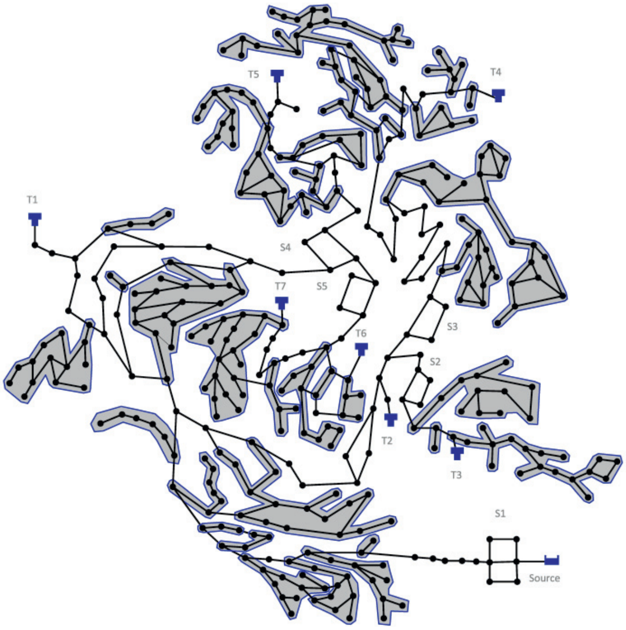

Fig. 4. Main network and subareas definition.

5.2. Global optimization process

Once the optimized subareas have been added to the whole model, an optimization process will be used to search for the optimal pump scheduling which minimized the objective function. A Pseudo-Genetic Algorithm (PGA) was used for the optimization. Details of the PGA can be read in [1]. The values of the parameters β_i were chosen so the penalty were of the same magnitude of the rest of the terms, but higher. For instance, if the level in a tank at the end of simulation is lower than the initial level, it was assumed that the corresponding pumping station have to deliver the remaining volume with low efficiency and at the peak hour price. So the algorithm will correct this effect without external intervention. After the global optimization process is fulfilled, a new, optimized model of the network is available. Then, a fine adjustment will be performed.

5.3. Post-processing

With the new network, a fine adjustments will be made using BMPs. This post-processing includes pump replacement, as stated in previous paragraphs and assessment of VRPs behavior. As valve setting were made considering the subareas as isolated network, the result of the subareas addition to the main network may cause distortion in the results. So, some corrections were made to the new model. On one hand, the valve setting is a continuous variable, while the PGA deals with discrete variable. The pressure setting obtained during the optimization process can be modified to improve the results, that is, to reduce background leakage, mainly. These changes may provoke small variation in the network behavior, which may cause constraints violations. The settings are improved to fit the minimum pressure in the critical node in every subarea. Then, a single run is performed to ensure that all the constraints are satisfied. After these improvements, the new network is assessed again in order to determine if there is a need for a new optimization loop. Eventually, a subarea definition may be needed. In that case, the new network becomes another basic network and the loop starts again. When there are no changes in the subarea definition, the process is finished and the network is assumed the final solution.

6. Summary of Results

The result of the optimization presents some important facts:

- 416 from 432 pipes have to be changed, which supposes 96% of the total. This is due to the high environmental price of background leakage.
- As a result of applying equation (3), pumps PU3, PU4, PU7, PU8, and PU11 were not used and left only for emergency purposes.
- According equation (4), pumps PU2 and PU6 were substituted by new ones.
- A total of 61 pressure control valves are to be installed.

A summary of results of the final solution can be seen in Table 3.

7. Discussion of results and conclusions

Some significant aspects of the solution applied to BBLAWN in this work are:

- The initial network was clearly oversized, both in pipe diameters and in pumping capacity. This has caused that a great part of the system has been resized. Also in every pumping station one of the pumps has been completely stopped.
- The inability of performing time controls in pumps has made very difficult to adjust pumping costs to the proposed electric tariff.
- Demands and leakage flow have been sometimes small. As EPANET base its convergence in continuity balance, the results are highly sensitive to precision.

- Optimization model has been very useful. Nevertheless, the number of DVs was very so a methodology was needed to solve the problem. Applying alternatively the optimization model to main network and subareas, the reduction on the number of DVs has been possible.
- EPANET model calculates the exact instant in which pumps switch on or off. Therefore, this causes differences in leakage flows depending on the hydraulic model formulation. When using EPANET approach for switching events, the environmental cost associate to leakage is 488,405.00 €. This is the cost expressed in Table 3. However, if the pump status is maintained along the whole time step, the value above becomes 496,568.10 €.

In summary, combined application of optimization techniques (PGA) and manual adjustment based on the use of BMPs has been shown to be suitable for solving a generic problem of water supply networks: the reduction of water losses due to background leakages.

Table 3. Summary of results.

Concept	Number of Elements
1. Operational costs	
1.1. Background leakages	488,405.00 €
1.2. Energy consumption	168,118.00 €
2. Capital costs	
2.1. Pipe replacement	566,975.33 €
2.2. Pump renewal	8,472.00 €
2.3. Control valves	20,115.00 €
Total Cost	**1,252,085.33 €**

Acknowledgements

This work was supported by the project DPI2009-13674 (OPERAGUA) of the Dirección General de Investigación y Gestión del Plan Nacional de I + D + I del Ministerio de Ciencia e Innovación, Spain.

References

[1] D. Mora-Meliá; P.L. Iglesias-Rey; F.J. Martínez-Solano; V.S. Fuertes-Miquel. Design of Water Distribution Networks using a Pseudo-Genetic Algorithm and Sensitivity of Genetic Operators. Water Resour Manage 27 (2013) 4149–4162.

[2] L.A. Rossman. EPANET 2.0 User's manual. EPA/600/R-00/057, 2000.

[3] A. Marchi and other 64 authors. The Battle of the Water Networks II (BWN-II), Journal of Water Resources Planning and Management, 140 (2014) 1-14.

[4] G. Germanopoulos, A technical note on the inclusion of pressure dependent demand and leakage terms in water supply network models Civil Engineering Systems. 2 (1985) 171-179.

[5] P.L. Iglesias-Rey, F.J. Martinez-Solano, D. Mora-Melia, J.V. Ribelles-Aguilar, The battle water networks II: Combination of meta-heuristc technics with the concept of setpoint function in water network optimization algorithms, In Proceedings of the 14th Water Distribution Systems Analysis Conference, A.C.T.: Engineers Australia, Sydney, 2012, 510-523.