Methodology for the development of projects to improve the water and energy efficiency of supply networks using a heuristic optimization model

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ABSTRACT

The scarcity of water resources the increase in energy costs have generated, in recent years, an increase in the number of projects to improve the hydraulic and energy efficiency of water distribution networks (WDN). This paper presents a methodology for these projects based on a hydraulic model of the network and the use of a heuristic algorithm. The methodology uses as a starting point a calibrated model of the WDN, where leaks are explicitly considered as pressure-driven demands. Subsequently, the model is simplified in order to reduce calculation times. From this point, the heuristic algorithm is used, considering as possible actions on the WDN: improve pumps operation, close pipes, rehabilitate pipes and install pressure reducing valves. The methodology has been applied to the WDN of L'Olleria (Valencia) showing that an adequate combination of the decision variables allows to find a balance between water saving, energy consumption and investment costs.

INTRODUCTION

Climate change is having a great impact on available water resources and is generating problems of water scarcity and sometimes an increase in energy costs associated with hydroelectric energy production. Climate change has also had impact on the water resources and its effects leads to a decrease in the amount of fresh water available. On the other hand, there has been an increase in the population in cities, focusing the need for water even more in cities, based on demographic growth (Bocquenet et al. 2016). In addition to water stress factors, there is an increase in electricity tariffs during recent years, based on changes in the prices of fossil fuels and the reduction of the rainy season due to climate change. These have been determining factors in the costs and quality of the potable water service worldwide. Therefore, water and energy optimization projects have become critical for the management of water supply networks (WSN).

Nowadays, there is a growing trend towards the development of optimization tools for improving the efficiency of water distribution networks (WDN), and this optimization can be carried out based on multiple methodologies. However, their results cannot be applied properly and truthfully without a properly calibrated model. Models are decisive tools in the decision making related to the design, optimization and simulation of the WDN. However, these models are often made incorrectly due to lack of information, the additional costs involved, or the lack of updating of the modifications made over the years, and therefore do not represent the actual conditions. For this reason, optimization tasks of a model incorrectly calibrated are inefficient, and will not provide the expected results in relation to the reduction of leaks and energy costs.

This paper presents a methodology that combines the development, calibration and simplification of a mathematical model of an RDA with the subsequent use of an optimization heuristic algorithm to improve the water and energy efficiency of a water distribution system (WDS). For this purpose, a particularly careful representation of leakage flows is performed, which are represented as pressure-driven demands.

After the basic construction of the mathematical model, several techniques of model calibration and simplification are applied. Subsequently, after simplifying the network, the optimization heuristic algorithm developed determines the best combination of the pumps operation and the reference pressures of the pressure reducing valves (PRVs). The purpose is to find a balance between water consumption, energy consumption and investment cost. Finally, the method is applied to the case of the WDN of L'Olleria (Valencia, Spain).

METHODOLOGY

In this section, the proposed methodology for the development of projects that aim to improve the energy efficiency or water improvement of any SDA will be described in detail. Figure 1 illustrates the general scheme of the methodology proposed in this document. This methodology identifies the procedures and the different stages that must be developed to meet the objectives set.

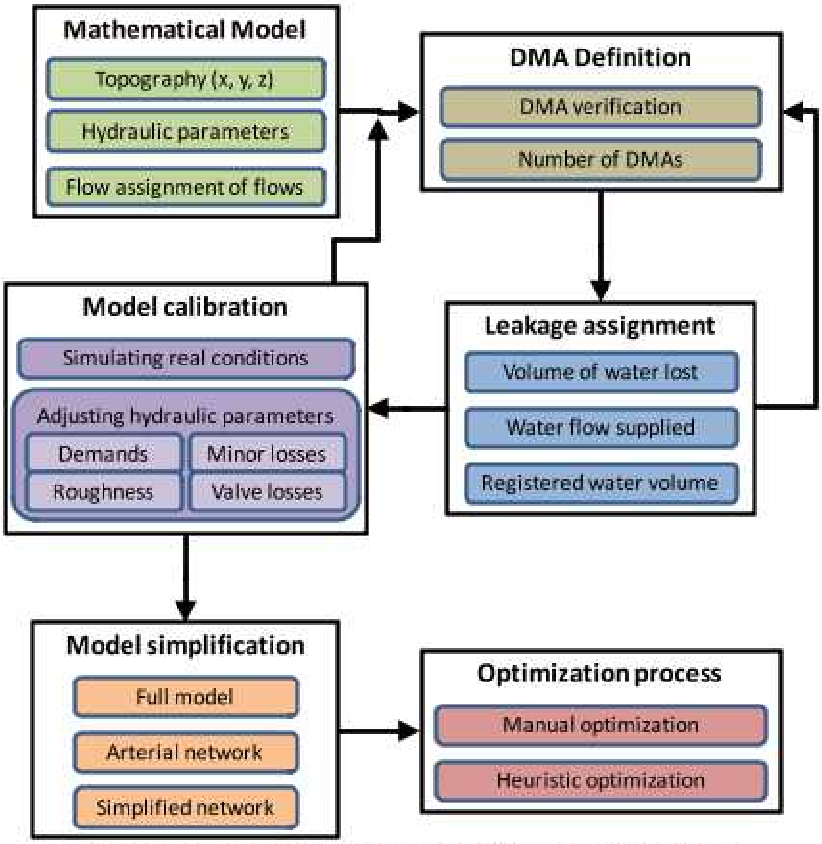

Figure 1. General flowchart of the methodology

The first phase of the methodology consists in the development of the mathematical model of the network. In this case, EPANET model (Rossman 2000) was chosen as hydraulic simulator. This phase consists of three different stages. In the first one, it is necessary to define the topographic information of the area. It is essential to guarantee the correct execution of this stage, since with this information the pipes length and elevation of demand nodes will be established. The origin of this information could be multiple: digital plans, geographic information systems or documentation held by WDN managers. The second stage focuses on establishing the hydraulic characteristics of the network. For the pipes, aspects such as the internal diameter or roughness are fundamental; for the valves, diameter and operating instructions; and for pumps, their head and performance curves. This information usually requires on-site visits to the facilities, since it is often not available. The third stage focuses on the allocation of flows, whether they are dependent or independent of pressure. The analysis of the available water billing data allows allocating the non pressure driven demands (NPDDs). This analysis requires evaluating the volumes injected in the system, the different categories of water use, the information of the meter and its periodicity of invoicing (Robinson et al. 2005). In addition to this process, it is possible to extract the volume of losses from the network that will later be assigned to the nodes through a specific methodology (Martínez-Solano et al. 2017).

The second phase focuses on the definition of the sectors in which the network will be divided. This subdivision of the network allows better control of the consumed flows, adequately detect the level of losses of each of the areas of the RDA and properly distribute the leaks as consumption dependent on pressure. Additionally, the sectorization is fundamental not only to simplify the optimization and calibration processes of the network, but it is also considered one of the best methodologies for the control of leaks in the supply networks. This phase will allow the application of specific techniques for controlling the escaped volume (Martínez Solano et al. 2018).

The third phase of the methodology consists in assigning leaks to the model. A model represented without considering its leakage does not faithfully represent reality. Frequently the losses are represented in the models as NPDDs. However, this technique does not allow to see the effects of the implementation of leakage reduction programs based on the reduction of pressures. For this reason, in this methodology a model representing leakages as pressure driven demands (PDDs) is used (Martínez-Solano et al. 2017). In the development of this phase it is necessary to make some hypotheses: the volume supplied to the network is known, water losses of the WDN correspond to PDDs and all District Metering Areas (DMAs) have flow meters at their entrance. That is, the network is divided into DMAs so that in each of them water billing and instant injected flow are known. The parameters to be calibrated in this methodology are the global coefficient representing the behavior of the PDDs (henceforth emitters) and the demand pattern of the NPDDs. The initial demand pattern is assumed to follow the same pattern as the flow supplied. With this hypothesis, the average pressure and leakage flow of each sector is calculated. If the value of the lost volume modeled does not match the real value, it is necessary to perform an iterative process by correcting the global coefficient of the emitters until obtaining a valid error in the difference between the real and modeled values. Then it is necessary to correct the demand pattern, where it is necessary in order to obtain in the model the same volume of leakage as obtained from the data. Finally, the verification of the leaked volumes will be carried out, and the emitting coefficient will be corrected if necessary up to an acceptable tolerance.

The fourth phase corresponds to the calibration process whose objective is to adjust the physical characteristics of the main elements to match real data. The variables that are adjusted during calibration are: filling levels of tanks, verification of tank inlet and outlet connections, elimination of non-existing pipe connections, representation of pipes not reflected in the initial model, etc. It is necessary to perform a rigorous analysis of the data before it is used, especially in relation to the filtering of the measurements obtained from the SCADA system. As a final step in the calibration process, a simplified macro-model of the main network is carried out. In this stage the tank levels previously calibrated and NPDDs of each sector must be used. With this model, it is sought to obtain the roughness coefficients of the main pipelines, in order to complete the calibration of the model.

As a fifth phase, it is necessary to simplify the network. The aim is to optimize simulation times in the subsequent optimization stage. Several simplification methodologies are used: data purification, elimination of branched sections, grouping of pseudonodes, joining lines with identical properties. The combined use of these simplification methodologies generates better efficiencies in the skeletonization process than the isolated use of only one of these techniques (Oyarzun 2011). At the end of this phase there will be 3 different models: a complete network, an arterial and a simplified network. The first one is used to validate and verify any action that is carried out on the network. The arterial network represents only the main pipes, which is why it is suitable for optimizations considering only elements in it. Finally, the simplified network includes a schematic form of the complete network that contains, in addition to the main pipes, all the necessary elements to adequately represent the network. This last model is decisive in the optimization phase, since it is the only one that allows to optimize the reference pressures of the PRVs installed at the entrance of each DMA.

The last phase corresponding to the optimization of the model will be carried out by means of heuristic techniques based on a pseudogenetic optimization algorithm (Mora-Melia et al. 2013) and whose adaptability to other optimization models has been already demonstrated (Iglesias-Rey et al., 2016, Martínez Solano et al., 2018). In this case, the objective function proposed aims to minimize the electrical energy consumed:

$$\sum_{i=1}^{T}\sum_{j=1}^{NB}\frac{\gamma * Q_{ij} * H_{ij}}{\eta_{ij}} * \Delta t_i * C_i + \lambda_1 * \sum_{i=1}^{Ndep}(Z_{ini_i} - Z_{fni_i}) + \sum_{i=1}^{Nnod}\sum_{j=1}^{T}\lambda_{ij} * (P_{ij_{min}} - P_{ij}) \qquad (1)$$

In the previous equation the first term represents the energy cost. Thus, T is the final time of the simulation, NB is the number of pumps in the system, C_i is the cost of the electricity tariff in each of the periods considered; Δt_i is the duration of each analysis interval; γ is the specific weight of water; while Q_{ij}, H_{ij} and η_{ij} respectively represent the flow, head and performance of each pump j at time i.

The optimization model aims to guarantee two basic operating conditions: guarantee the minimum pressure in each node and guarantee recursivity of tank levels (that is, final tank level should be at least equal to the initial one). Therefore, the objective function adds two additional terms. The first is a penalty in the case of not verifying the recursivity in tanks. Thus, λ_1 is the penalty factor related to the tank levels applied to the difference between the initial and final level of each tank. The second term is the penalty for not verifying the minimum pressure at nodes. The term λ_{ij} corresponds to the penalty factor related to the minimum pressures required, adopting a null value in the case of verifying the minimum pressure and adopting a value that is considerably high so that the model discards those solutions with low pressures.

Within the optimization process, the decision variables are: the starting and stopping instructions of each of the pump, and the setpoint for each PRV. The consideration of electric energy as an objective guarantees both energy efficiency and water efficiency. The energy efficiency is direct since the model directly optimizes electrical energy. However, the reduction of losses indirectly implies a reduction in water consumption, which in turn leads to a reduction in the objective function.

CASE STUDY

In order to verify the methodology described in the previous section, it has been applied to the case of the Water Supply Network of L'Olleria (Valencia). This WDN has two pumping systems (one well and one booster for the high zone) and four tanks connected together two to two so that only two storage points are defined: Ermita tank and Cuerna tank. Each point has a circular and rectangular structure with a total storage capacity of 840 m³ in Cuerna and 2871 m³ in Ermita. The bigger tank is fed by the well and supplies water to the two main DMAs: the industrial area and the town center area. On the other hand, Cuerna tank feeds two other small DMAs (Llobero and disseminated area). Galim area, located near the town center, can be supplied by any tank according to the installation. However, the connection pipe between this zone and the disseminated is disabled.

According to the water billing data and production information, the network currently has an approximate volumetric efficiency of 65%, which is a relatively low value for a network that has a high number of DMAs (32 in total). Figure 2 shows the general scheme of network.

Figure 2. SCADA of the L'Olleria water supply network

Following the methodology described, the initial model of L'Olleria network is obtained Figure 3). Topographic and hydraulic characteristics were established based on the information supplied by the water company (EGEVASA). Initially the distribution of the flows between the nodes was made using a criterion based on the unit flow of each street. However, this generated numerous nodes where flow was zero. Therefore, the initial distribution of the base demands was modified reviewing the available information and the cartography.

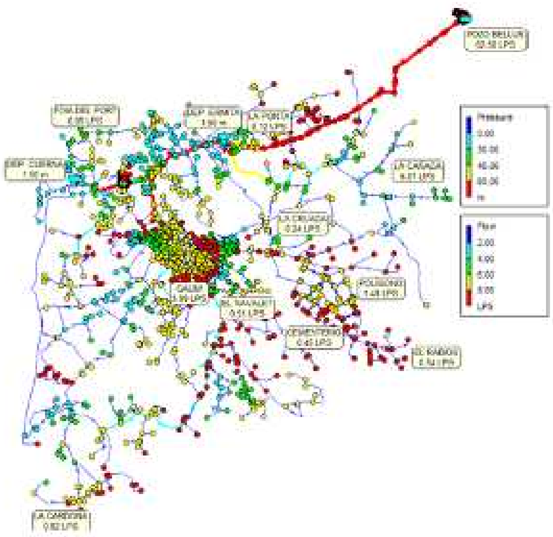

Figure 3. Original model of the L'Olleria network

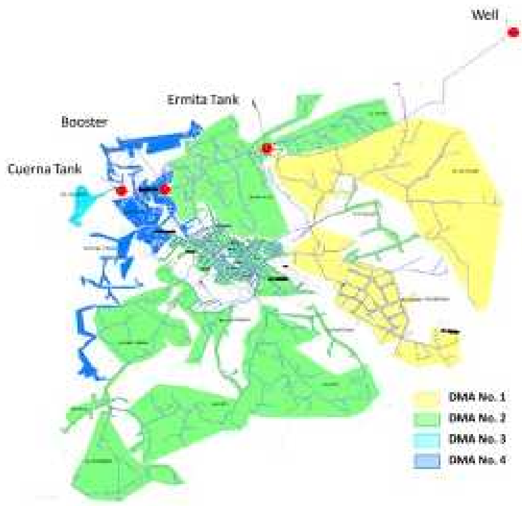

Figure 4. Final distribution of DMAs of L'Olleria network.

In the second phase and in order to define the sectors, it was necessary a previous revision and verification of the sectorization, which was particularly complex due to the large number of existing sectors. The final result of this analysis was the detection of incorrect isolation of 8 of the 32 sectors. Taking into account the large number of hydrometric sectors proposed in the initial model, their incorrect operation and high operating costs, it was necessary to carry out a redistribution of the hydrometric sectors based on the areas with continuous measurement. Thus, number of hydrometric sectors finally used has been 4 (Figure 4).

After the network sectorization, the third phase of the methodology is the calibration process. For this process, the information available from SCADA (software used for remote data recording and control of the network) was used. The analysis of the information is done carefully as it presented problems such as: lack of data in certain periods, inconsistency of some values due to absence or change of the measuring instrument, erroneous readings due to failures in electronic communication. After the analysis and filtering of the data, it was decided to select as reference day for the study on June 26, 2017.

The distribution network model initially available, did not have a representation of PDDs (system leaks). For this reason it was necessary to develop the fourth phase of the proposed methodology. Modeling of water losses is based on the simultaneous calibration of leaks and demands. It was necessary to adjust the demand factor of the entire network (0.93), since the invoiced flow did not match the modeled. The difference between real and modeled leakage flows is low (0.00%, 0.15%, 0.32% and 0.06% on each DMA), and a fast confluence was obtained after two iterative processes in each segment. By means of the process of PDDs, there is a significant problem of leakage 3 DMAs, with leakage percentages corresponding to 50.2%, 88.9% and 36.5% of the total flow injected into each area. Figure 5 shows the results obtained from DMA 2. It can be shown the rapid confluence of the injected flow.

Figure 5. Supplied flow - DMA 2.

Once the leaks are modeled, it is necessary to execute the fifth phase of the methodology, corresponding to the calibration. In this phase it is necessary to verify the behavior of the network and its congruence with the actual measured values. In case of not being valid, a deep analysis of the measured data and its coherence is required. For the specific case of the L'Olleria network, an error was detected in the time of the measurements of the deposits and pumping, which made a fast and correct calibration difficult. Figure 5 shows the levels of the deposits recorded in the continuous measurement system and the levels calculated according to the registered flows. A displacement of 45 minutes is observed in the discharge flows to the pumping system and sector 2 from the Hermitage deposit and the refominated flow to the Cuerna deposit.

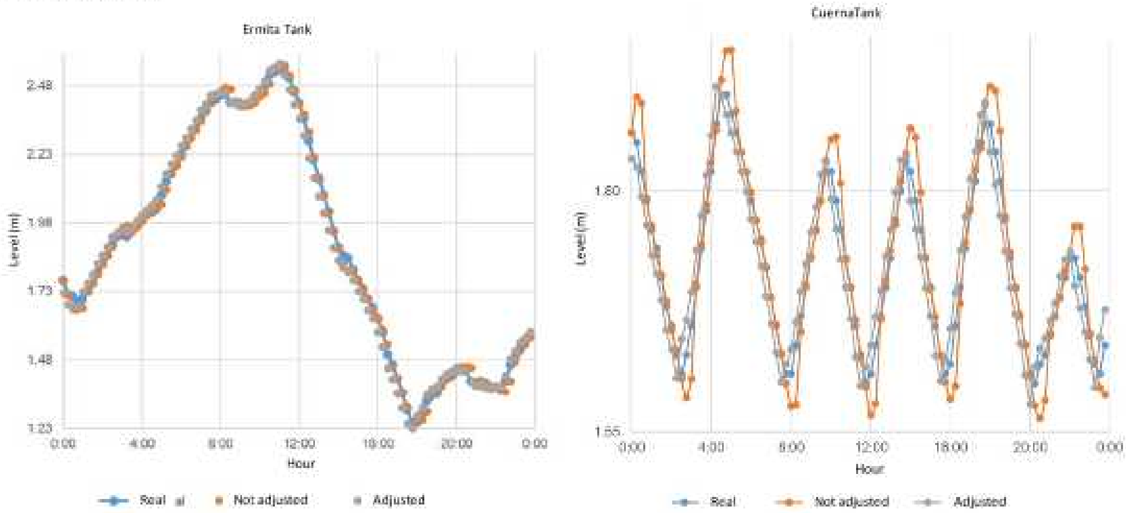

Figure 6. Tank level comparison

In the final stage of the calibration phase, the levels of the tanks previously calibrated for the arterial network are used. The value of the roughness coefficient of the main pipes are adjusted by an iterative process. The model obtained represents adequately the behavior of the network, although it detects that there are problems of high pressures in different areas.

In short, the calibration process of a model is complex and demanding in the initial stage. The degree of difficulty is generally based on lack of network information, data incorrectly measured, incorrect sectorization definition and the status of the initial model. Figure 7and Figure 8 show the flow rates for pump flows and tank levels respectively. The figures represent actual measurement (obtained from the SCADA), the results of the initial model and the calibrated model.

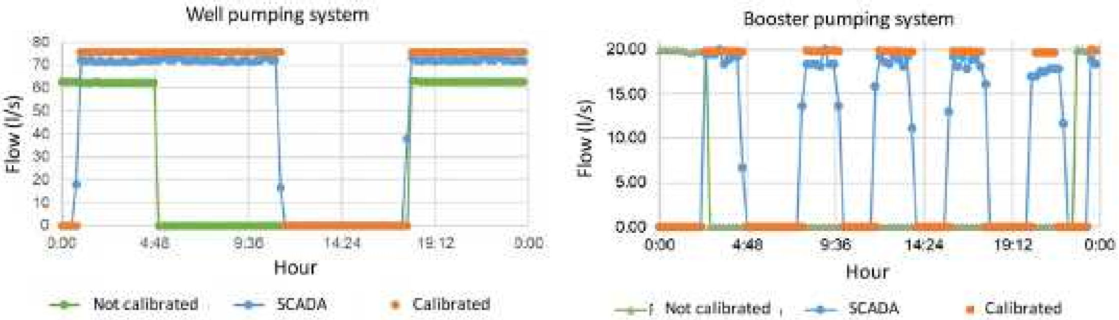

Figure 7. Comparison of pumped flows (Calibration)

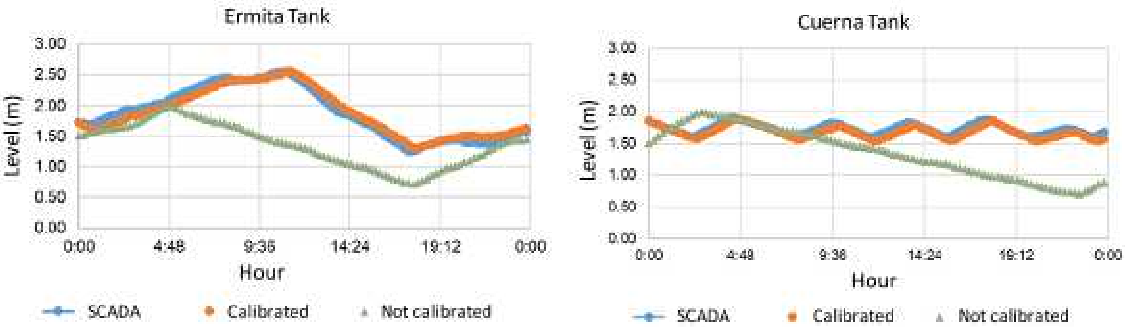

Figure 8. Comparison of tank levels (Calibration)

Once the calibration has been carried out successfully, the next stage of the process is the simplification of the network. The main simplification techniques used to reduce the size of the WDN model of L'olleria are: i) elimination of branched branches; ii) grouping of pseudonodes; and iii)joining of pipes with the same hydraulic characteristics. For the case of the urban area it was difficult to simplify it because of the high degree of mesh. At the end of this process it was possible to simplify 62% of the network nodes and 61% of the pipelines, decreasing from 1679 to 635 nodes, and from 1828 to 719 lines.

The network simplifying process has been verified selecting different main elements and analyzing the behavior of the complete and the simplified model. Figure 9 and Figure 10 show pump flows and tank levels respectively considereing the real data obtained from the SCADA, the results of the complete model and the results of the simplified model. As can be seen, there is a close correlation between the complete and the simplified model.

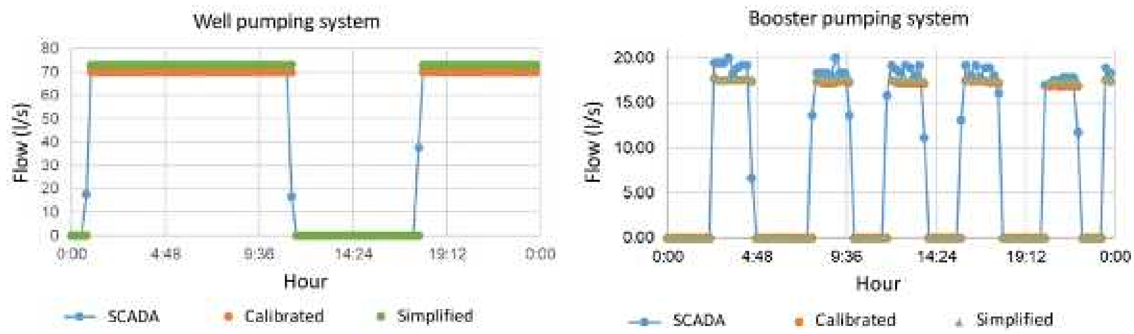

Figure 9. Comparison of pumped flows (Simplification)

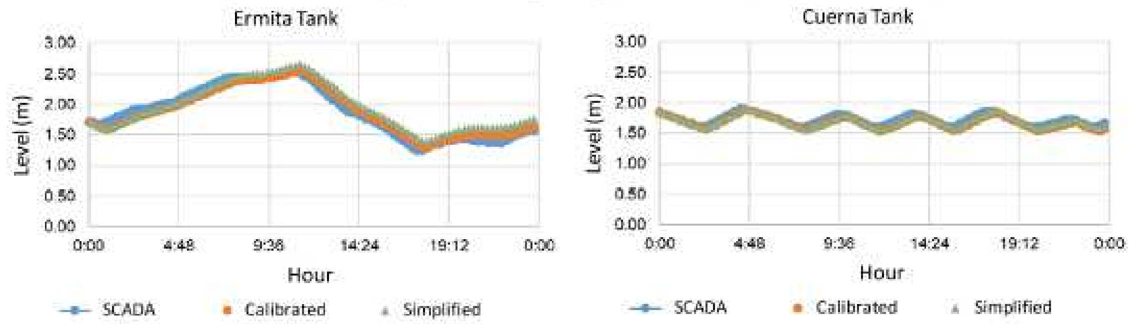

Figure 10. Comparison of deposit levels (Simplification)

The final phase of the methodology, corresponding to the optimization will be fundamental in the reduction of operating costs of the network. The correct calibration and simplification will guarantee that the theoretical values obtained in the optimization will result in a real monetary saving for the company.

For optimization, it is necessary to consider the variations over time of the electricity rates. As a first scenario, it is proposed to control the operation of the pumps based on the level of the tanks, so that each pump starts and stops controlled by the level of a tank. At the same time, it must be ensured that the tanks are not emptied and the pressures are higher than those required (25 mca for the network in general and 35 mca for the urban center).

The second scenario focuses on adjusting the pumps operation to electricity rates. In this way the pumps start and stop according to time and not to tank levels. Likewise, it is necessary to maintain the same restrictions as in the case of scenario 1. Figure 11 shows the results of the pumping costs obtained for the month of July. Water billing data correspond also to the month of July 2017 and were provided by the service provider company.

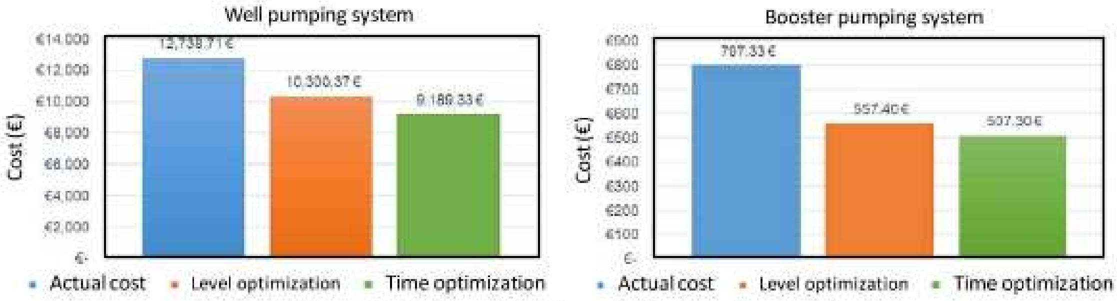

Figure 11. Electrical costs (Optimization)

It is clearly evident that the lower electrical cost is presented in the hourly optimization, corresponding to a saving of 30.09% of the pumping costs at the well and 19.14% at the booster pumping system. It is clear that the main factor in operating costs results from the well. Therefore, the optimization tasks were focused in this field. Additionally, it is necessary to analyze the water consumption, since it is essential to complete the optimization. Figure 12 shows the results obtained from the total volume injected during the month analyzed.

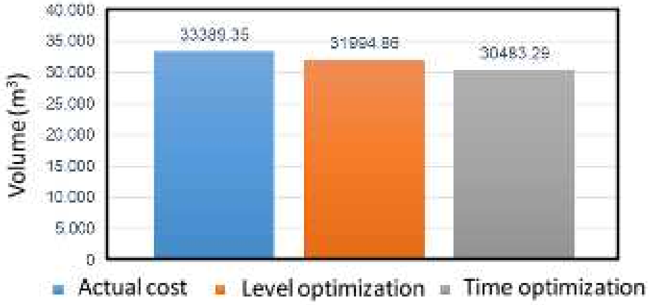

Figure 12. Total volume injected

As expected according to the cost analysis, the lowest injected volume is presented in the second optimization methodology, obtaining a saving of 8.70% of the total volume corresponding to 11,624m³ in one month of service.

CONCLUSIONS

From the analysis of the presented methodology and its application to the case study, the following conclusions can be drawn:

- The construction of the mathematical model of the network has been shown to be the a fundamental tool in the process of optimizing the operation of the network. In particular, EPANET model has shown to be effective in representing the behavior of the network under changing conditions of both pressures and flow rates.
- A fundamental aspect in both modeling and optimizing a water distribution network is the definition of sectors. In the analyzed case, it started from a situation of excessive number of sectors. In fact, 32 sectors for a population of 30,000 inhabitants were excessive. Moreover, such a complex system often tends to have malfunctions. Thus, the consideration of only 4 sectors has been enough to improve the behavior of the network both energetically and hydraulically.
- A key element in the proposed methodology is the allocation of leakage flows as PDDs. Thus, the model used modifying node emitters and demand pattern at the same time has been extremely effective in representing the behavior of the leakages in the network.
- The calibration of the network allowed to adjust the roughness coefficients of the main pipes. This process allowed to adjust the model to match real data obtained from the SCADA.
- Regarding the simplification process, it was possible to simplify the model by approximately 62%. This simplification was carried out mainly in area far from the city center with dispersed consumption. The simplification of the urban area was more complex as it was a highly meshed area with a large number of interconnections between the different nodes of the network.
- Once the optimization of the network was carried out using the proposed method, two different cases were analyzed: an optimization based on the tank levels and another based on time. In both cases, the values of the reference pressures of the PRVs were optimized.The final result shown a reduction of 30% in the costs of pumping and of 8.70% of the total volume injected.

In short, the proposed methodology has proved effective for improving the water and energy performance of a water supply. Undoubtedly, the case study analyzed has particularities. But, the method could be applied to any water distribution system with the same information requirements as those available for the case of L'Ollería.

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