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Simultaneous Calibration of Leakages, Demands and Losses from Measurements. Application to the Guayaquil Network (Ecuador)

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Abstract

Hydraulic models of water supply networks are widely used by utility companies to assist in decision making. The reliability of the model strongly depends on the quality of its calibration, that is, the correspondence between the measure variables and the calculated ones. When dealing the model is static, the calibration is easy to reach for average values of the variables. On the contrary, dynamic models need to spatially allocate demands and distribute them among the nodes of the network, which complicate the problem.

The paper proposes a methodology for preliminary calibration of hydraulic models based on advanced calibration techniques. This methodology is applied to models with both pressure-dependent and independent demands. Pressure-dependent demands are related to leakages and are spatially distributed according to the length of the pipes and volumetric efficiency of the district metering area (DMA) being considered. In order to model leakages, the Germanopoulos model has been chosen. Thus, leakage flow is a function of the length of the pipes and the pressure along them. The equation to quantify the volume of leakage is a modification of the orifice equation.

From this leakage model, a calibration process is proposed. It consists in three steps. First, a global leakage coefficient is calculated in order to satisfy daily mass balance of produced unaccounted and consumed water. In the second step, a time demand pattern is calculated. After these two steps a preliminary model is obtained. Finally, a conventional calibration process is done using discrepancies between pressure measurements and model result to adjust both roughness and minor losses coefficients.

In order to validate this calibration methodology, a case study was used in Guayaquil (Ecuador) in which three DMA were studied. The results showed that the method converges very quickly and is effective regardless the volumetric efficiency of the network.

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1. Introduction

Currently the hydraulic models of water supply networks are widely used by utility companies and consultants to assist in planning, design and assessment of the network. So, the more reliable is a model, the more useful.

The American Water Works Association (AWWA) states that the calibration is to compare the model results with measurements obtained in the field, making adjustments to the model parameters and review of field data to reach agreement between both [1]. According to Shamir and Howard [2] "*calibration is to determine the physical and operational characteristics of an existing system, which entered as data to allow for realistic computer model results*." Walski [3] defines calibration as a two-step process consisting of:

a) compare simulated pressures and flow rates with those observed (measured) for known conditions of operation, and
b) adjust the input data to the model so that there is agreement between the observed and simulated values

In short, the calibration of hydraulic models can be defined as the process of setting the parameters defining the hydraulic behavior of the model to reflect as accurately as possible the actual operation of the distribution network for both static and dynamic scenario.

This paper aims to present a methodology for calibration of mathematical models of water distribution networks for the allocation of consumption and pressure dependent demands (leaks) and minor losses in the network. Thus, actual demands and existing leaks will be distributed both spatially and temporally in the supply network. The methodology is completed with a case study corresponding to a hydraulic sector of water supply network in the city of Guayaquil in Ecuador.

2. Method

2.1. Problem statement

Next, a methodology for calibrating the network is proposed. The method adjusts the coefficients of the emitters, the demand pattern and the head losses in pipes. The methodology is based on a series of assumptions described below:

- The consumed water, that is, the demand, is considered independent of pressure in the network. Furthermore, its value is assumed to be known by means of metering.
- Inflow supplied from the water sources into the network is known, including its temporal variation. This implies that the total volume of non-revenue water is also known.
- The volume of non-revenue water will be composed of leaks in the network and therefore is considered dependent on the pressure.
- The effect of roughness and internal diameter reduction of the pipes can be represented by a single coefficient of roughness and a number of coefficients of minor losses in certain lines of the network.
- The network is assumed to be divided into district metering areas (DMA) with similar characteristics, both in pipes features and in the demand pattern.

As mentioned above, the methodology for model calibration considers as targets three parameters:

- A global coefficient for the emitters for the entire distribution network.
- The temporal time series that represents the demand pattern.

- The roughness in pipes and the minor losses coefficients for valves.

Next, the equations used by the method will be presented. As it usually happens in most water distribution networks, the supplied and consumed water are known. However, the temporal variation of the first is also known, but not the latter. The water balance can be written in the following manner:

$$Q_S(t) = \sum_{i=1}^{N_D} m_{D,i}(t) \cdot Q_{BD,i} + Q_L(t) \tag{1}$$

In equation (1), $Q_S(t)$ is the supplied water flow at time *t*; $Q_L(t)$ is the non-revenue water flow at time *t;* $m_{D,i}(t)$ is the demand pattern multiplier for node i at time *t.* ; $Q_{BD,i}$ is de base (average) demand for node i , and N_D is the number of demand nodes in the model. The simplest approach to modeling leaks is to admit that the leakage flow is dependent on the pressure at the point where they are located:

$$Q_{L,i}(t) = c_{E,i} \cdot p_i(t)^n \tag{2}$$

Where $p_i(t)$ is the pressure at node *i* at time *t*, *n* is the exponent used in the emitter and $c_{E,i}$ is the emitter coefficient for node *i.* With all this, the equation (1) can be expressed as the sum of the independent pressure demand (consumption) and dependent pressure demand (leakage). Extending this approach to all demand nodes, equation (1) may be re-written as a continuity balance at time *t*:

$$Q_S(t) = \sum_{i=1}^{N_D} m_{D,i}(t) \cdot \bar{Q}_{BD,i} + \sum_{i=1}^{N_D} c_{E,i} \cdot p_i(t)^n \tag{3}$$

Assuming that the simulation is divided into *T* time intervals, the number of unknowns is $N_D \cdot (T+1)$. Hence, same number of equations is needed. Equation (3) accounts for *T* equations (one for each time interval). Furthermore, the average value of demand pattern multipliers should be 1, completing the necessary number of equations. Admitting that all nodes have the same demand pattern within a DMA and have the same emitter coefficient the problem might be reduced to $T+1$ unknowns and the system is perfectly determined. In addition, for this study it is assumed that the exponent of the emitter is 0.5. Equation (3) will be:

$$Q_S(t) = m_D(t) \cdot \sum_{i=1}^{N_D} Q_{BD,i} + c_E \cdot \sum_{i=1}^{N_D} \sqrt{p_i(t)} \tag{4}$$

There is an implied relationship between the demand pattern, the emitter and the pressure at the nodes. This relationship is given by the hydraulic equations of the network and the EPANET program will be used to determine the value of the pressures once the demand pattern and the emitter coefficients have been fixed. This makes the problem iterative because it is necessary to give a value to the values of $m_D(t)$ and c_E to calculate the pressures, but it is also necessary to know the pressure to solve the system formed by equations (4). Next, the phases followed to solve the problem are described.

2.2. Global coefficient of emitters

First, the system of equations formed by equations (4) will be solved for each moment of calculation. The second term of this equation represents the calculated leakage flow in the network. The average value of this flow (Q_L) is known in advance by subtracting the demand flow from the supplied one.

In equation (4), in order to obtain an estimate of the emitter coefficient, only the variation of pressure through time needs to be known. However, to calculate the pressure it will be necessary to know exactly the time variation of demand. To do this, an initial hypothesis has been adopted which consists of assuming that the demand pattern follows the same pattern than the supplied flow. With this hypothesis pressures are calculated and an estimate of the average leakage rate is obtained. If the value does not match Q_L a new iteration will be done, correcting the global coefficient of emitters. This process is repeated until the differences of the values of pressures and leakage flow between two iterations are below a certain threshold error.

If there is sufficient information for different DMA, it could be considered the possibility of using a method to take into account the uneven spatial distribution of leaks in the various DMA of the network. In any case, the differentiation of the leakage depending of the DMA does not add new equations to the problem.

2.3. Demand pattern

Once the global coefficient of the emitters has been calculated, the value of each demand pattern multiplier can be obtained from the set of equations (4):

$$m_D(t) = \frac{Q_S(t) - c_E \cdot \sum_{i=1}^{N_D} \sqrt{p_i(t)}}{\sum_{i=1}^{N_D} Q_{BD,i}} \qquad (5)$$

Obviously, when modifying the demand pattern, pressures change slightly. So, this process should be repeated until the error observed between measured and simulated flow is small enough.

2.4. Head loss calibration

The calibration process for the head losses in the hydraulic model starts once both global coefficients for emitters and demand patterns multipliers have been obtained. This process involves adjusting the overall head losses in the model, that is, friction losses in all the pipes and minor losses in some pipes considered relevant to the hydraulic network performance. The calibration criterion seeks to minimize the difference between the observed and calculated values of pressures.

Finally, the adjustment of the losses necessarily affects the pressure distribution on the network. Therefore, once this third step in the calibration process has been completed, a new check on the balance of daily flows should be performed. If this test is positive, the calibration process will be completed successfully. Otherwise, the process will start again with new values for the coefficients of emitters, demand pattern multipliers and head losses coefficients. Figure 1 shows the steps followed in this calibration process.

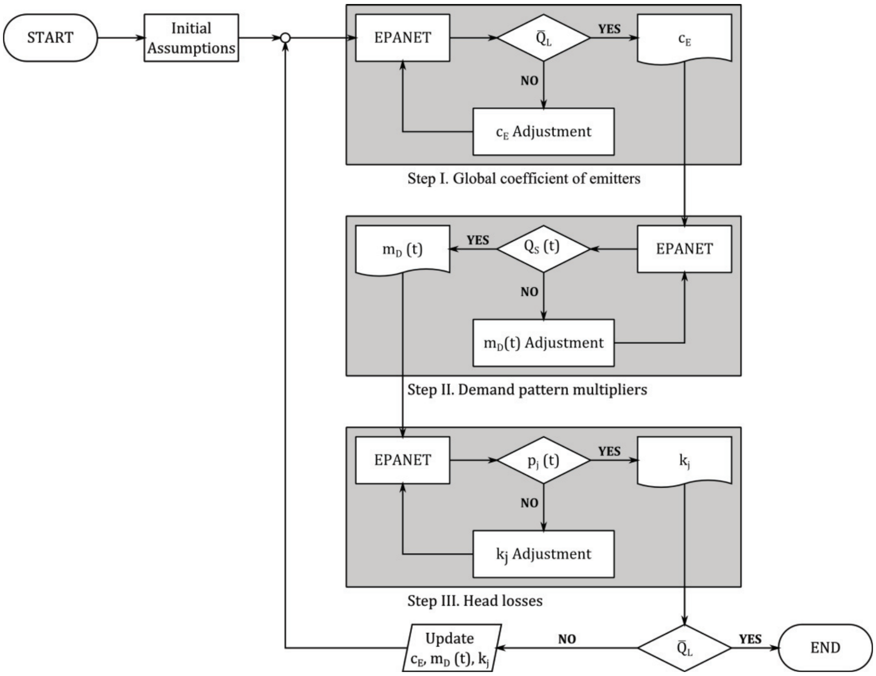

Fig. 1. Flow chart of the calibration process.

3. Case Study

The methodology described above has been applied to one of the districts of the water distribution network of Guayaquil (Ecuador). This district covers an area of 96 ha with 35 km of network pipes and 5672 users. Besides, this DMA presents a volumetric efficiency of 77.7%. The mathematical model of the network of this DMA has 252 nodes and 391 pipes. In addition, this district was divided into 4 sub-sectors for leakage control purposes, as shown in Figure 2. In the same figure, the points where pressure gauges has been installed are also shown.

For calibration of this case ten iterations were needed. Three of these corresponded to the adjustment of overall coefficient of the issuer; not necessary to perform the second calibration pattern of consumption after adjustment for losses in the network.

The first simulation corresponds to a preliminary simulation with no emitters. In this first simulation, no leakage was considered and the results were used to obtain the average value of the pressure. The first estimate of the global coefficient for emitters was obtained from this pressure, leading a value of 1.4274 $l/(s\cdot mca^{0.5})$. This value was proportionally distributed among the 251 existing nodes using length of connecting pipes as stated by Germanopoulos [4]. From simulation 4 on, the demand pattern was already defined. Simulation 7 corresponds to the first spatial distribution of leakage, and in the simulation 8 the head losses calibration of the network was performed. Finally, the simulation 10 corresponds to final adjustment of the global value of emitters, whose value was $l/(s\cdot mca^{0.5})$. Between each of the above simulations it was necessary to adjust the global value of emitters.

Fig. 2. Hydraulic model for the DMA N72 (Guayaquil, Ecuador).

Figure 3 shows graphically the results of measurement test made in subdivision District N72-M132. These tests were made to obtain the corresponding minimum night flow to each of the four hydraulic sub-sectors and the results were used to spatially distribute leakages.

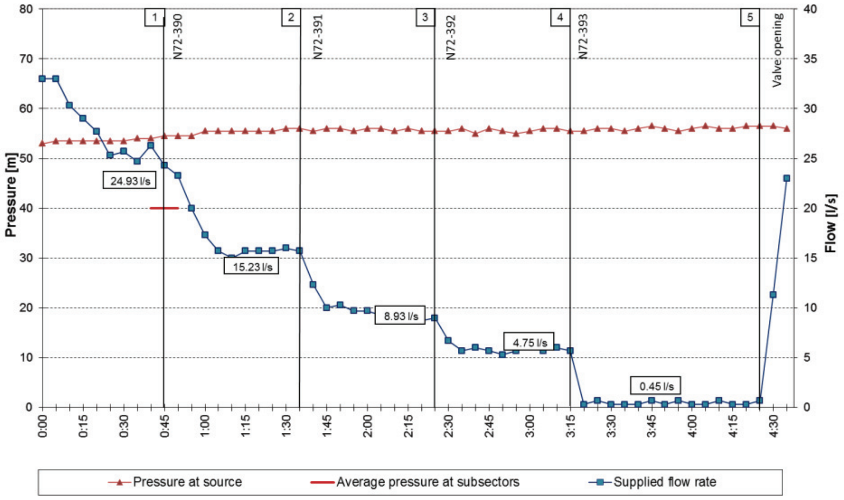

Fig. 3. Subdivision test for DMA N72.

For calibration of the head losses in the network, apart from the roughness of the pipes, 6 pipes were selected to have important minor losses due to the presence of partially closed valves. Besides, another valve near the node N-5 (Sector N72-390) was defined set as 'closed'. The following graphs correlate values between simulated and observed flow rates in link L-157 at the entrance of the subdivision N72-390 for the first simulation (Figure 4) and at the end of the process (Figure 5). It can be observed the fitness of both values.

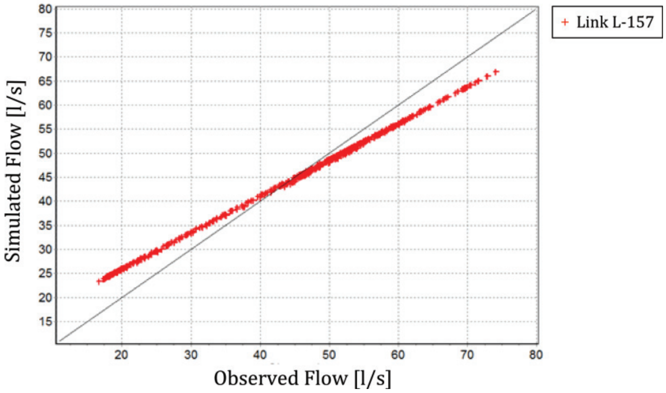

Fig. 4. Correlation between flow rate values after simulation 1.

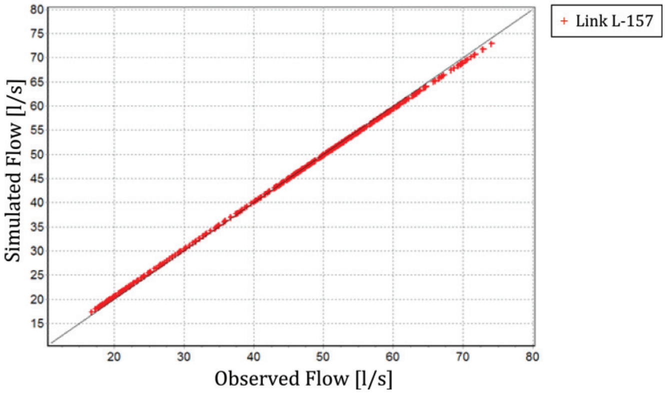

Fig. 5. Correlation between flow rate values at the end of the process.

Finally, in Figure 6 the correlation between pressures at different nodes of the network after the process is also presented. The average relative error in the case of pressure is slightly bigger (between 3.9% for node N-5 and 0.85% for node N-183).

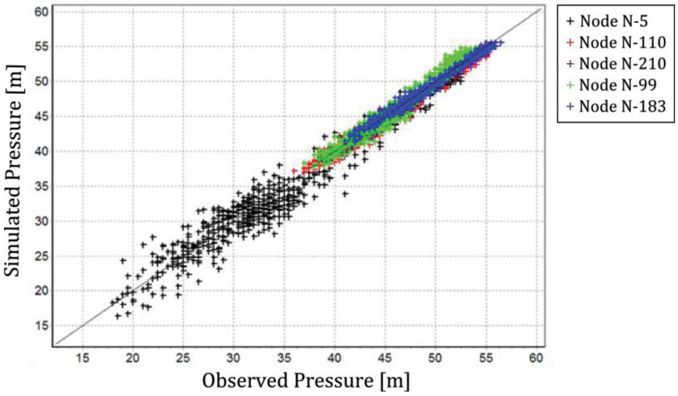

Fig. 6. Correlation between pressures at different points at the end of the process.

4. Conclusions

The most important contributions that can be concluded from this study include:

- The iterative method presented in this paper has a rapid convergence and therefore is an alternative to using complex mathematical optimization techniques. Its usage might simplify the problem of calibration of hydraulic models.
- The proposed method allows a preliminary calibration of hydraulic models in networks with limited availability of information regarding flow and pressure measurements.
- In cases where there is an inability to perform field tests to estimate the values of the coefficients of head losses, this method allows represent them as minor losses. This in turn allows including the lack of reliable information on the position of the valves installed in the distribution network during the calibration of the model.
- Adjustment of demand pattern from the temporal variation of leakage is also achieved.
- Use of emitters to represent pressure-dependent demands such as leaks has been incorporated. In this way, it is possible to obtain a better approximation of the hydraulic model to the real conditions of operation of the network.
- Finally, in order to validate the methodology, it has been applied to a case study pertaining to water supply system of the city of Guayaquil (Ecuador). The method has shown rapid convergence and high accuracy in a few iterations.

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