11th International Conference on Hydroinformatics
HIC 2014, New York City, USA

COMPARISON OF DEMAND PATTERN CALIBRATION IN WATER DISTRIBUTION NETWORKS WITH GEOGRAPHIC AND NON-GEOGRAPHIC PARAMETERIZATION

GERARD SANZ ESTAPÉ, RAMON PÉREZ MAGRANÉ (1)
(1): Department of Automatic Control, Polytechnic University of Catalonia, Terrassa, Spain

Demands are one of the most uncertain parameters in water distribution network models. A good calibration of the model demands leads to better results when using the model for any purpose. A demand pattern calibration methodology that uses a priori information has been developed for calibrating the behavior of demand groups. In cities, similar demand behaviors are distributed all over the network, contrary to smaller villages where demands are clearly sectorised in residential neighborhoods, commercial zones and industrial sectors. In this work, demand pattern calibration has a final use for leakage detection and isolation. Detecting a leakage in a pattern that covers nodes spread all over the network makes the isolation unfeasible. Besides, demands in the same zone may be more similar due to the common pressure of the area rather than for the type of contract. A demand pattern calibration methodology is applied to a real network with synthetic non-geographic demands for calibrating geographic demand patterns. The results are compared with a previous work where the calibrated patterns were the original non-geographic ones.

INTRODUCTION

Water distribution network models are widely used by water companies. The availability of a good calibrated model is a key factor when applying methodologies using it. Generally, pipes roughness and nodal demands are calibrated. Savic *et. al.* [6] reviewed the water distribution network calibration problem.

Sanz and Pérez [4] proposed a demand calibration methodology based on [7] and [8]. The Singular Value Decomposition (SVD) of the sensitivity matrix was used for the calculation of the calibrated parameters correction in an iterative scheme. Nodal demands where estimated through the calibration of demand patterns. The definition of these demand patterns was based in the consumers' types of contract, which were spread all over the network.

Leakage isolation methodologies [3] can be applied to the calibrated model. Nevertheless, the calibration process cannot be used directly for isolating leakages as the estimated parameters are not defined geographically. This work proposes the calibration of geographic demand patterns as a first approach for a future leakage isolation methodology. Results obtained with synthetic data are compared with the ones in [4].

METHODOLOGY

Generalized inverse problem

The objective of the calibration problem is to find the parameter vector x that minimizes the errors $\mathcal{E}=y_m-y_p$, where y_m and y_p are the vectors of measured and predicted values, respectively. In non-linear systems, a correction in the parameters Δx is calculated iteratively and used to correct the parameter vector x, as detailed in Eq. 1.

$$S \cdot \Delta x = \varepsilon$$
$$x_{r+1} = x_r + \rho \cdot \Delta x_r \tag{1}$$

where S is the sensitivity matrix that relates errors in predictions with errors in the models parameters; r is the current iteration; and ρ is a parameter to control the step size. The iterative scheme is continued until a termination criterion is achieved.

Singular value decomposition

The SVD is capable of solving under-, over-, even- or mixed-determined problems with no rank conditions in S, as explained by Menke [2]. The SVD of matrix S is

$$S = U \cdot \Lambda \cdot V^T \tag{2}$$

where U is an m x m matrix of orthonormal singular vectors associated with the m observed data; V is an n x n matrix of orthonormal singular vectors associated with the n system parameters; and Λ is an m x n matrix of the singular values of S. The SVD is used to solve Eq. 1 as shown in Eq. 3.

$$\Delta x = V \Lambda^{-1} U^T \cdot \varepsilon \tag{3}$$

The V matrix is also used for the estimation of the covariance matrix Υ^2 of the parameter space.

$$\Upsilon^2 = V \frac{\sigma^2}{\Lambda^2} V^T \cdot \varepsilon \tag{4}$$

where σ^2 is the variance of the measurements, considered to be the same for all sensors. The diagonal elements of Υ are estimates of the uncertainty (standard error) of the estimated parameters.

Demand calibration in water distribution networks

The application of this calibration methodology to water distribution networks consists in estimating the nodal demands of the network in order to minimize the error on the available measurements. Both pressure and flow sensors are considered, so the sensitivity matrix for each type of measurement has to be computed. Cheng and He [1] proposed the calculation of the sensitivity matrix from the system energy and mass continuity equations. The correction of demands ΔD depending on head prediction errors ΔH can be computed as seen in Eq. 5.

$$BCB^T(H_p + \Delta H) = (D_p + \Delta D)$$
$$BCB^T \Delta H = \Delta D$$
$$\Delta H = A^{-1} \Delta D \tag{5}$$

where B is the incidence matrix of the network; C is the non-linear matrix depending on the pipes roughness, lengths, diameters and hydraulic gradient; H_p is the predicted head vector; D_p is the predicted nodal demand vector; and $A=BCB^T$. Similarly, the correction of demands ΔD depending on flow prediction errors ΔQ can be calculated as

$$
\begin{aligned}
&(Q_p + \Delta Q) = CB^T(H_p + \Delta H) \\
&\Delta Q = CB^T \Delta H \\
&\Delta Q = CB^T A^{-1} \Delta D
\end{aligned} \tag{6}
$$

where Q_p is the predicted flow vector. Matrices A_{mh} and A_{mf} are generated by selecting the rows of A^{-1} and CB^TA^{-1} respectively, corresponding to the measured heads and flows. Merging both matrices and adding a water balance equation, the whole system is defined (Eq. 7). Weights are added in order to unify units, and SVD is used to compute ΔD.

$$
W \begin{vmatrix} A_{mh} \\ A_{mf} \\ 1\ 1 \ldots 1 \end{vmatrix} \Delta D = W \begin{vmatrix} \Delta H_{mh} \\ \Delta Q_{mf} \\ 0 \end{vmatrix} \tag{7}
$$

The calibration of thousands of nodal demands with only few measurements leads to an under-determined system of equations. A new parameterization can be done by associating each nodal demand to a determined behavior (demand pattern). The weight of each demand within its pattern (base demand) is obtained from billing. The new parameterization is defined as

$$
D(t) = BDM \cdot TPM \cdot P(t) \cdot q_{in}(t) \tag{8}
$$

where BDM is the Base Demand Matrix, a diagonal n x n matrix containing the base demand values of each node; TPM is the Type of Pattern Matrix, an n x k matrix associating each initial parameter (nodal demand) to a unique new parameter (demand pattern); $P(t)$ is a vector containing k patterns at sample t; and $q_{in}(t)$ is the total inflow of the network. Eq. 7 can now be defined depending on the pattern correction ΔP.

$$
W \begin{vmatrix} A_{mh} \\ A_{mf} \\ 1\ 1 \ldots 1 \end{vmatrix} \cdot BDM \cdot TPM \cdot \Delta P(t) \cdot q_{in}(t) = W \begin{vmatrix} \Delta H_{mh} \\ \Delta Q_{mf} \\ 0 \end{vmatrix} \tag{9}
$$

Eq. 9 includes the system equations for a single time instant. Additional equations from other samples can be added if similar boundary conditions in the system are considered, reducing the uncertainty on the calibrated parameters. Notice that these additional equations do not increase the rank of the system, but filter uncertainties in it.

CASE STUDY

The calibration methodology explained in the previous section is applied to a real network with synthetic data. The network is a District Metered Area (DMA) situated in the Barcelona neighborhood of Nova Icaria. It is composed by 3455 pipes and 3377 junctions. The water is provided from a transport network through two pressure reduction valves. Pressure and flow is monitored at both water inlets with a sample time of one hour. The structure of the network is depicted in Fig. 1.

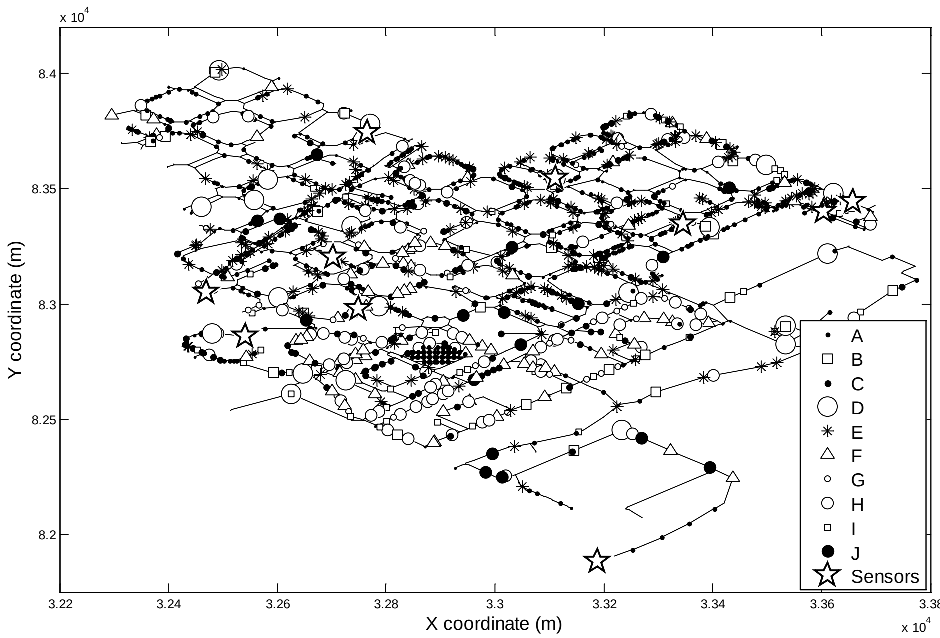

Figure 1. Nova Icaria water distribution network model with non-geographic patterns

A synthetic demand model based on Eq. 8 has been generated. Real billing data have been used to set the base demands of the synthetic model. Next, ten patterns have been defined, representing different types of contracts: industrial, restaurant, commercial, etc. A unique pattern has been assigned to each nodal demand. Subsequently, a random noise $N(0,0.1 \cdot d_i(t))$ has been added to each demand at each sample, where $d_i(t)$ is the consumption of node i at sample t without noise. As a 95% of the demand is within the 1.96σ boundaries, the added noise can be up to approximately a 20% of the expected demand value. An example of two nodal demands with and without noise is depicted in Fig. 2.

In this work, two different calibration approaches have been used. The first one consists in the calibration of the contract-based patterns, which are spread all over the network with a non-geographic distribution, as seen in Fig. 1. This distribution is the one used to generate the synthetic data. On the other hand, the second approach calibrates the same number of patterns, but defined using the information provided by the sensitivity matrix. The description of this methodology is presented in [5]. The resulting patterns have a geographic distribution (Fig. 3) due to the inclusion of topographic information in the generation of the sensitivity matrix.

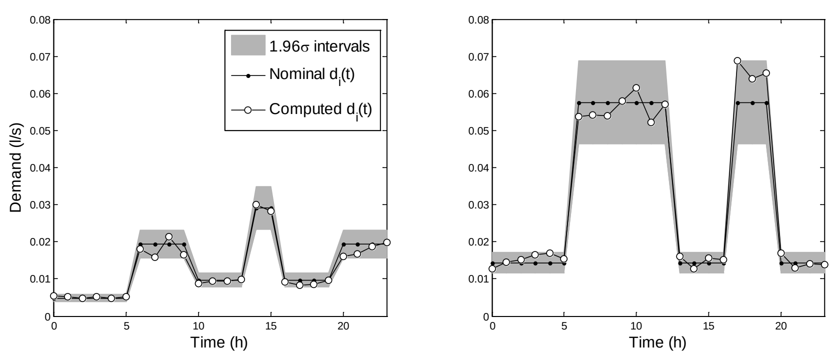

Figure 2. Example of two noisy nodal demands generation

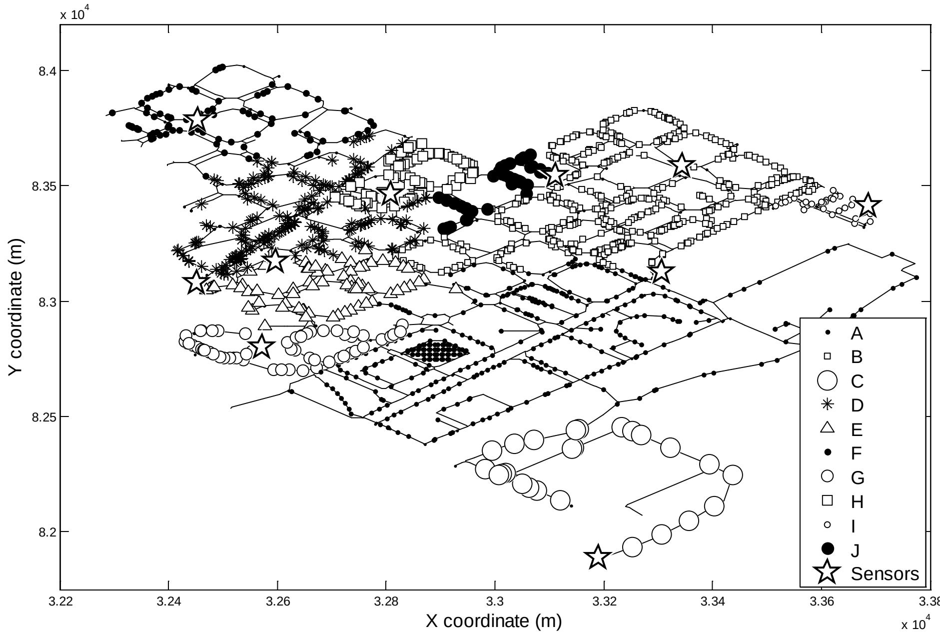

Figure 3. Geographic patterns and sensor distribution

A pressure sensor selection process for distributing the most sensitive sensors is performed for each approach. This sensor selection methodology is based in the information density matrix analysis detailed in [5]. In this work only pressure measurements are considered, as the company experts assessed that this type of sensors are the most used in water distribution networks for their lower cost and greater confidence when compared with flow sensors. A random noise *N(0,0.001m)* has been added to the sensors measurements in order to simulate the uncertainty of the real sensors. The sensors locations for both approaches are depicted with a star marker in Fig. 1 and Fig. 3.

A comparison of the accumulated consumed water of each pattern for both approaches is summed up in Table 1. Notice that the non-geographic distribution has a dominant pattern consuming five times more than the second one. On the other hand, the geographic distribution has a progressive reduction on the patterns consumption, with the highest pattern consuming twice the water of the second one.

The calibration methodology has been applied to calibrate 24 hours demand patterns. Five days of data (weekdays) have been used. It is considered that all five days have similar pattern values at each hour, so the extra data used would minimize the uncertainty due to the system non-linearity, demand inherent noise and sensors precision.

Table 1. Patterns water consumption for each approach

Pattern ID	***A***	***B***	***C***	***D***	***E***	***F***	***G***	***H***	***I***	***J***
Non-Geographic	40.7%	8,7%	8,1%	7,9%	7,3%	6,3%	5,8%	5,4%	5,3%	4,1%
Geographic	37%	18,2%	12,7%	9,4%	7,6%	5,6%	4,6%	2%	1,5%	1%

RESULTS

This section presents the calibration results when using the methodology on the synthetic network. Although results are obtained in a simulated scenario, the comparison is performed with the same indicators than in a real case: predicted pressures, estimated accumulated demand, and uncertainty in calibrated patterns.

A first comparison between the predicted and measured pressures is done. No figures are shown because in both cases (non-geographic and geographic) the maximum error on predicted pressures is very low (2 cm).

The second analysis consists in comparing the accumulated water consumptions of the calibrated patterns with the assumed ones. These consumptions are obtained from the sum of the accumulated demands of all nodes belonging to the same pattern. The assumed accumulated demand of a node is obtained from billing, while the calibrated one can be computed with the estimated pattern values. Fig. 4 represents the normalized accumulated pattern consumptions obtained from the assumed values and the calibrated ones. It is interesting to see how the geographic patterns accomplish precisely with the assumed values, while the non-geographic calibration generates higher errors.

The third indicator to be compared is the uncertainty in the calibrated patterns. High uncertainties are not desired because changes in patterns due to faults in the network would not be observed unless these changes fall outside the confidence intervals. Fig. 5 depicts the calibrated pattern values for the non-geographic (columns 1 and 2) and geographic (columns 3 and 4) patterns. It can be seen that a high uncertainty appears in all patterns of the non-geographic case excepting the one with highest consumption. On the other hand, uncertainties of the geographic calibration are lower, keeping the pattern shape visible.

Finally, it can be seen also in Fig. 4 that in the non-geographic calibration negative pattern values appear, which will not be accepted. That does not happen in the geographic calibration.

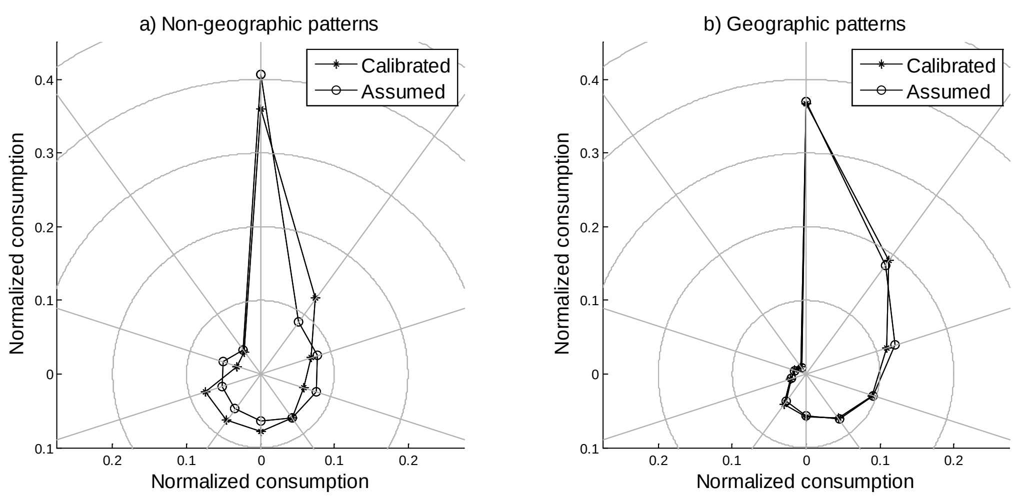

Figure 4. Normalized accumulated pattern consumptions

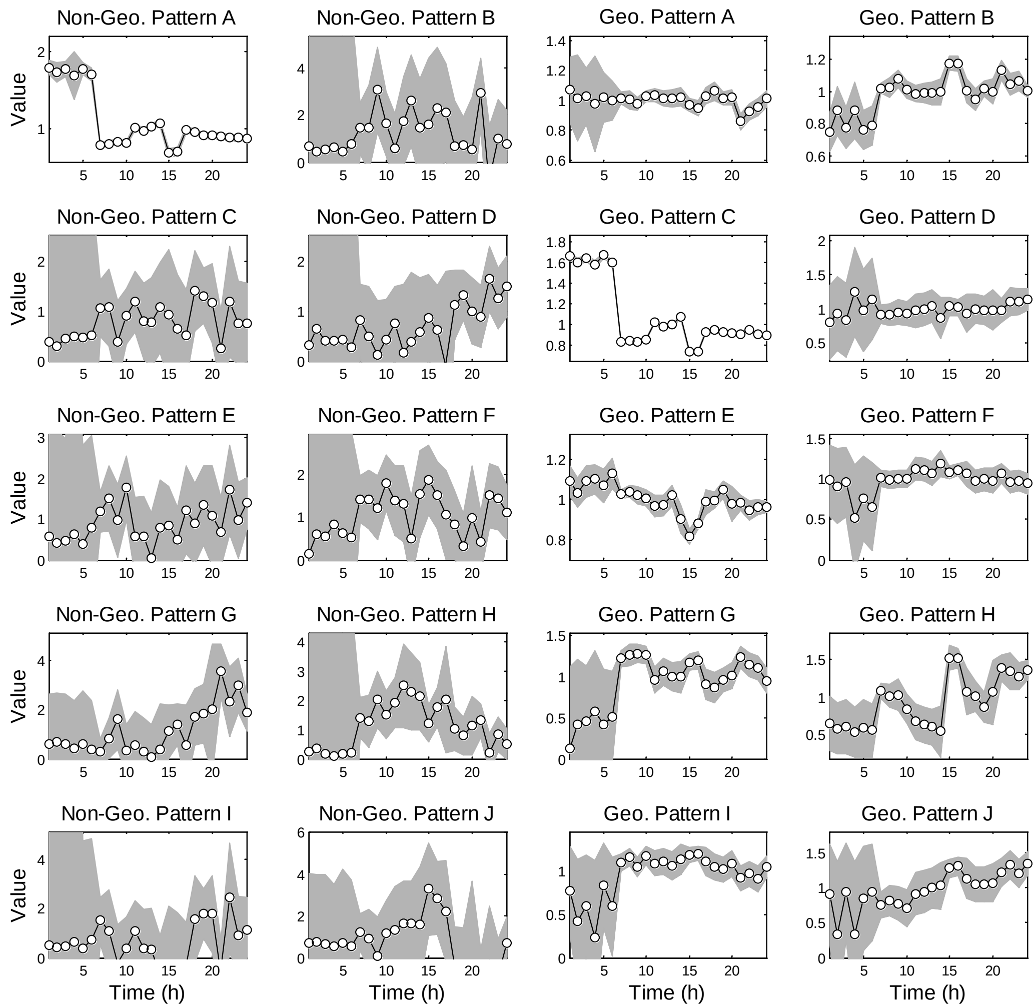

Figure 5. Calibrated patterns for non-geographic and geographic pattern distribution

CONCLUSIONS

This work is part of an underdevelopment thesis which main objective is to calibrate demands in water distribution networks while discerning between leakage appearance and demand evolution. Complementary works explaining parameterization, sampling design and calibration methodologies are cited and used as a base for the comparison presented in this work. Geographic allocation of patterns is desired for the leakage isolation objective. Non-geographic distribution of patterns makes unfeasible the isolation of a fault observed through a non-expected calibrated pattern value.

First, a brief review of the calibration methodology has been presented. A real network with synthetic data has been used to compare the results when considering geographic and non-geographic demand pattern distribution. The synthetic data used simulates a reality with a non-geographic demand distribution. The comparison between both approaches has been performed using the same indicators than in a real case: sensors pressures, accumulated pattern demand and uncertainty in calibrated values.

The results obtained when applying the calibration methodology show that both models have nearly perfect pressure predictions, although five samples from different weekdays have been used to calibrate each pattern value. However, the conservation of the accumulated consumed demand of each pattern and the uncertainty in the calibrated pattern values are better in the geographic distribution.

The better results obtained with the geographic approach can be explained by the effect of patterns changes in sensors. In the geographic distribution, each sensor is highly sensitive to a unique pattern, reducing the uncertainty in the calibrated values. However, in the non-geographic case each sensor is affected by nearly all patterns. This fact introduces uncertainty in the calibrated model.

As a main conclusion, the geographic pattern calibration generates better results. Besides, it is suitable for the final objective of detecting and isolating leakages. Furthermore, it has been seen that the indicators used to compare both scenarios give an estimation of the goodness of the calibration results.

ACKNOWLEDGMENTS

This work was supported in part by the project DPI-2009-13744 (WATMAN) and DPI-2011-26243 (SHERECS) of the Spanish Ministry of Education; by the project FP7-ICT-2012-318556 (EFFINET) of the European Commission; and by the Polytechnic University of Catalonia. The model and measurements of the Nova Icaria network were provided by the Barcelona water company AGBAR.

REFERENCES

[1] *Cheng W. and He Z., "Calibration of Nodal Demand in Water Distribution Systems", Journal of Water Resources Planning and Management, Vol. 137, No. 1 (2011), pp. 31–40.*

[2] *Menke W., "Geophysical Data Analysis: Discrete Inverse Theory", Academic Press, (1982).*

[3] *Pérez R., Quevedo J., Puig V., Nejjari F., Cugueró M., Sanz G. and Mirats J., "Leakage isolation in water distribution networks: A comparative study of two methodologies on a real case study", 19th Mediterranean Conference on Control & Automation, Corfu (2011).*

[4] *Sanz G. and Pérez R., "Demand Pattern Calibration in Water Distribution Networks", Proc. 12th International Conference on Computing and Control for the Water Industry, Perugia (2013).*

[5] *Sanz G. and Pérez R., "Parameterization and Sampling Design for Water Networks Demand Calibration using the Singular Value Decomposition: Application to a Real Network", Proc. 11th International Conference on Hydroinformatics, New York (2014).*

[6] *Savic D., Kapelan Z. and Jonkergouw P., "Quo vadis water distribution model calibration?", Urban Water Journal, Vol. 6, No. 1 (2009), pp 3–22.*

[7] *Uhrhammer R., "Analysis of Small Seismographic Station Networks", Bulleting of the Seismological Society of America, Vol. 70, No. 4 (1980), pp 1369–1379.*

[8] *Wasantha Lal A., "Calibration of Riverbed Roughness", Journal of Hydraulic Engineering, Vol. 121, No. 9 (1995), pp 664–671.*