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Water Distribution Network Models Calibration: Alternative Method (CNM) for Identifying Monitoring Stations

Henrique da Silva Pizzo[1], Edevar Luvizotto Júnior[2], Renata Mendes Rosa da Silva[3]
[1]Laboratory of Hydraulics, Estácio Juiz de Fora University Center, Juiz de Fora, Brazil
[1]Municipal Sanitation Company, Juiz de Fora, Brazil
[2]Laboratory of Computational Hydraulics, School of Civil Engineering, Architecture and Urban Design, University of Campinas, Campinas, Brazil
[3]Department of Sanitary and Environmental Engineering, Federal University of Juiz de Fora, Juiz de Fora, Brazil
([1]henriquepizzo.estacio@gmail.com, [2]edevar@fec.unicamp.br, [3]renata.mendes@engenharia.ufjf.br)

Abstract-The process of gauging input data in a model is called model calibration. The present work approaches the calibration of models of water distribution networks, and the parameter to be calibrated is the roughness coefficient of the pipes. To this end, pressure measures are taken at some points in the network to be compared with the results of the model. However, it is known that the quantity and positioning of these points chosen for monitoring can greatly influence the quality of calibration results, inducing errors. In this sense, to optimize the results, an alternative method is proposed for the identification and selection of these points. The method is applied to a hydraulic network, presenting very satisfactory results.

Keywords*- Model Calibration, Monitoring Stations, Inverse Methods, Hydraulic Networks, Water Supply*

I. INTRODUCTION

Mathematical models of simulation of hydraulic supply systems are tools which objective is to reproduce, through a computer, with the greatest possible accuracy, the actual behavior of the physical system it represents. However, it is not necessary for the model to reproduce all the physical components of the system, but perhaps only the most significant ones, depending on the reliability required and the use for which the model is intended. García-Serra [1] defines the mathematical model of a network as an abstraction of the real physical system, that intends, through a formulation with greater or lesser degree of complexity, to simulate the system's response to the desired situations. In practice, the modeling of a network is summed up as the study of simplified scheme itself, to which the appropriate parameters are associated to reproduce, as faithfully as possible, its effective behavior. The model pipes can correspond to actual pipes or to a certain association of them, so that certain quantities (roughness of the conduits) that appear in the model do not necessarily have to match their totality (curves, connections, valves, etc., existing in the set of pipes are modeled). Regulatory elements, pumping stations, etc. are also represented. On the other hand, the nodes, defined by the intersections of pipelines in the model, can correspond to a confluence of pipes approximately close, a consumption applied in place of an unimportant branch, a large consumption point, etc.

According to Walski [2], a computational model of a water distribution system is composed of a set of equations, and it predicts the pressures and flows in that system. However, the results of a model are only as accurate as the data that were input. Although it is possible to accurately identify the length and diameter of the pipes, other variables necessary for the program such as flow distribution and roughness coefficients of the pipes are not well known for the system, defining what is called model calibration. The possibilities are:

- To assume the pipes' roughness coefficients and the distribution of flows as correct and adjust the piezometric dimensions.
- To assume piezometric dimensions and roughness as correct and adjust the estimative of flow distribution.
- To assume the flow distribution and estimative of piezometric dimensions as correct and adjust the roughness coefficients.

As accurate and better elaborate as the simulator model is, it will not be effective in providing results of pressures and/or flows consistent with the real ones if the input data in this model are not the real ones. It is at this point that the need for an effective calibration is endorsed to examine the input data before the simulation stage is indeed started.

The static approach is used in the so-called classical methodologies, in which the characterization of fluid flow, considered incompressible, is made based on the equations of mass and energy conservation and a law of resistance to flow. Effects of inertia and elasticity are not considered. The numerical solution of the methods that use the static approach, in most cases, remains on the linearization and solution of the resulting system of equations. Koelle et al. [3], observe that the process of linear equation solutions in their general matrix form [A].[x] = [B] is common to various engineering fields. It is well known in the technical literature that, in some cases, depending on the values of the component elements of the matrix [A], inaccuracies occur in the determination of the values of the unknowns that compose the matrix [x]. In a specific case study of a real hydraulic installation, it is observed that, although there were no convergence problems with the linear theory method used in the solution of the problem, the results were erroneous and, only by investigating them, it was possible to verify the fact of the poor conditioning of the matrix that comprised the representative system of equations of the flow in the installation.

The elastic approach is based on the use of equations of mass conservation and the amount of movement, generalized in such a way as to characterize the flows, in a permanent regime and in variable regime (transitory or oscillatory). Although the basis of the use of this technique in the analysis of the permanent regime has been proposed for a long time, only a few decades ago, with the advent of new research and computational advances, it has come to be considered an extremely powerful tool for this type of analysis.

The Time Marching Approach – TMA, to be employed in this work, has the advantage of being a method that presents a physical convergence (supposedly real) in time, through a hypothetical transient, reaching the final permanent regime. This is not the case for other methods widely used in water networks, such as Cross, Newton-Raphson, Linear, Gradient, and others, which contemplate a simply numerical approximation.

Another advantage of the TMA model is that it already works with hydraulic transient equations, so it is ready to be used in calibration cases performed on a transient regime.

According to Solomatine [4], although genetic algorithms are preferred for problems related to water resources, other global (or multi-extreme) algorithms are also used. Solomatine [4] points out that many users are uninformed of the existence of these other algorithms, which may be more efficient and effective than genetic ones. He compares nine of these algorithms in terms of effectiveness (accuracy), efficiency (required number of function evaluations - relative to computation time), and reliability (percentage of algorithm hits). Two of the algorithms researched (ACCO and CRS4) showed better behavior than the genetic. Other experiments related to the reference show that, for certain problem classes with highly discrete variables, for example, in the optimization of water distribution networks, the genetic algorithm, due to its discrete nature, may actually be more accurate than other algorithms developed for continuous variables. Still, in nearly all problems with continuous variables where the genetics were used, other global optimization algorithms can also be applied.

According to Wright [5], from 1990 onwards there has been a resumption of interest in non-derivative optimization methods, especially for problems in which function evaluations are very onerous or complex, not allowing exact or approximate derivatives to be calculated at reasonable cost. It points to a growing need for research in the area, since such methods of direct search, especially Nelder-Mead and its variations, have been widely used, despite serious deficiencies in theory and performance.

Ferreri et al. [6] propose a method to evaluate pipe roughness coefficients, using pressure and flow measurements at selected points of the network. The method is based on the system of continuity and energy equations for permanent regime. Such a system, which is nonlinear, is solved by using the Newton-Raphson method, and the measuring points are chosen by sensitivity analysis.

Regarding the calibration process itself, including measurement activities, the difficulties inherent to the process arise, already detected in the need of several field teams and measuring devices, and others of a more theoretical nature, and present another important challenge to be faced.

Therefore, regarding the number of points to be monitored, in the case adopted here, the pressure value (monitoring stations), it is convenient to have as few stations as possible, if they are sufficient to ensure a good calibration. In this case, it would be avoided: expenses with displacement of several field teams, the need for several pressure recording devices (since it is ideal that the measurements are simultaneous) and other operational difficulties that could even make the process unfeasible.

II. The Hydraulic Model TMA

The general equations that determine liquid flow in closed pipelines are hyperbolic partial differential equations, without analytical solution. They are, respectively, the equation of continuity (1) and the equation of the amount of movement (2).

$$\frac{\partial H}{\partial t} + \frac{a^2}{g\,A}\frac{\partial Q}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial Q}{\partial t} + g\,A\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2DA} = 0 \qquad (2)$$

where H is the hydraulic head, t is time, a is celerity, g is gravitational acceleration, A is the area of the cross section of the pipe, Q is the flow, x is the space, f is the friction factor, and D is the diameter of the pipe.

According to Chaudhry apud [3] several numerical and graphic techniques of solution for this system of equations have already been proposed, and the method of characteristics is the most used technique, for several advantages.

The elastic approach is traditional in the analysis of transient regimes, however, due to the general nature of their equations, it also allows the analysis of permanent flows.

The time marching approach is a technique for determining the real permanent regime as a result of a hypothetical transient situation created by the modeler. The technique was widely explored by Shimada [7] and Luvizotto Jr. [8], among others, who mention that it is a fact that the convergence to the permanent regime through the transitory regime can be quite slow, which has motivated some researchers to seek procedures to accelerate it. Shimada [7] points out that, although requiring greater computational effort than the more direct methods, the TMA model is sometimes preferred for performing permanent or transient analysis in the same way and for being able to produce different permanent regimes only by changing the boundary conditions. Luvizotto Jr. [8] presents applications of the method also for extensive period, and points out that the main advantage over other methods of network calculation, as verified, such as linear theory and Newton-Raphson theory, is its physical convergence, when following the transitory evolution, to the detriment of the numerical iterative process of the other methods, not counting the fact that these are matrices, resulting in a sequence of solutions of systems of equations, which have particularities for resolution that should always be observed. Another advantage of the TMA model is that the method can also be applied to situations of non-permanent regime since the component equations are those of hydraulic transient. The hydraulic simulator, based on the TMA model, also used in the research that generated the present work, was the SPERTS model.

III. The Nelder-Mead Optimizator

In order to develop a calibration model, it is interesting that an algorithm for searching for extreme points of functions is allied to the hydraulic simulator, to ensure the convergence process between the hydraulic model and physical reality. The result of this association is called the hybrid model. The equation to be used, known as objective function or merit function, works with the difference between measured values and simulated values, a difference that must be minimized so that the values given by the model are as close to the actual model as possible. The scheme is presented as follows, according to equation (3):

$$\min x^2 = \sum_{i=1}^{N} \frac{\left(V_i^* - V_i\right)^2}{\sigma_i^2} \quad (3)$$

where:

x^2 – objective function;

V_i^* – measured value;

V_i – simulated value;

N – number of monitored points;

σ – standard deviation.

Taba apud [9] suggests that, in theory, the search process can be treated through two distinct sets of methods:

- Direct search methods: they are used in the process only values of the objective function. They are applied when the function is discontinuous and non-differentiable, when derivatives are difficult to calculate, or for previous approximations.
- Differential methods: they use the value of the objective function and its partial derivatives of first and second order in the search process.

Wright [5] mentions that direct search methods were initially suggested in the 1950s and continued to be proposed during the following decade in a reasonable amount. Such methods were typically presented and justified more by their geometric intuition than by mathematical theory. Thus, the emergence of new algorithms was motivated in an attempt to overcome certain inefficiencies of previous methods. He cites that the most famous direct search method, based on a simplex, was proposed in Nelder and Mead in 1965 [10]. The Nelder-Mead method is based on the creation of a dynamic simplex, continuously modified by established rules, so that it best adapts to the local configuration.

The simplex is a geometric figure of N dimensions, consisting of N+1 vertices and all the line segments that interconnect them, the polygonal faces, etc., known as convex polyhedron.

In [10] there is the introduction of an ingenious idea for the search for optimal operating conditions by evaluating the output values of a system in a series of points forming a simplex in the doable region of research, and continuously forming new simplexes, through the reflection of a point in the space of the remains. This idea is clearly applicable to mathematical problems of minimizing functions of several variables. However, according to the conception of Spendley et al. [10], the steps to be taken for the variation of the factors at stake were already known and determined, which made the strategy somewhat rigid for general use.

In the Nelder-Mead method, also described in [10], which bears the authors' name, the simplex adapts itself to the local configuration, extending in research regions where long inclined planes are formed, changing direction in angled regions, and contracting in the vicinity of a minimum point. There is no need to make assumptions about the search surface, except that it is continuous and has a single minimum in the search area. An important property of the method is that it converges even when the initial simplex lies between two or more minimum points (valleys) of the search direction, property that is not common to some other methods.

Pizzo and Luvizotto Jr. [11] use the hybrid model for pipe roughness calibration. Luvizotto Jr. [12] uses the Nelder-Mead procedure also to detect leaks in water distribution systems, and Pizzo and Luvizoto Jr. [13] use it for demand calibration, with very expressive results, using the hydraulic simulator SPERTS, generating a hybrid model.

Reference [14] presents the development of a computational routine that considers the losses by leakage and the dependence of demands with pressure, associated to the hydraulic simulator EPANET 2, using hypothetical network data for calibration in terms of absolute roughness and parameters of the leak model. For this, it is used inverse models solved with the support of genetic algorithms (GA) technology and hybrid procedure (GA and Simplex Method - Nelder and Mead).

IV. The Importance of Choosing Monitoring Stations

It is known that the quantity and positioning of the points chosen for monitoring can greatly influence the quality of calibration results. Thus, contrary to what may initially seem, not always that the calculated pressure values are equal to those of monitored pressure (objective function equal to zero), necessarily the calculation roughness values, which led to the final pressures, are equal to the actual roughness values. Therefore, it is important to obtain a good procedure for satisfactory identification (quantity and positioning) of the monitoring points, to avoid the possibility of masking the actual result.

Riguetto [15] presents a hydraulic model integrated with an optimization model based on genetic algorithms, in order to calibrate flow values in the nodes and branches, and roughness of pipes, obtaining good results. He points out that the correct identification of these monitoring stations is the key to achieving good results with the calibration model. He mentions that, for networks with hundreds of nodes and branches, it is necessary to select the most important ones, prioritizing the peripheral nodes and distant from the supply points, and the most important branches, considering the level of dependence of the nodal demands in relation to each branch of the network.

De Schaetzen et al. apud [16] cite an identification method and they apply it to the determination of monitoring points for the calibration of water distribution networks. The problem presented is the optimization of a fitness function, composed of the criteria of sensitivity and maximum entropy, being the optimizer based on genetic algorithms.

Pizzo and Luvizotto Júnior [17] propose a method for identifying these points, known as the downstream node method, due to the high correlation between a given tube and its sequential node, which led to very satisfactory results.

According to [18], much importance is given to determining the input data for water distribution system networks, particularly regarding urban networks, because their design and management are based on verification models. A good model calibration with realistic results can be obtained using a certain number of measurements: flow in pipes and pressure in nodes. It is presented the analysis of a new model able to provide guidance on the choice of measurement points to obtain the site's data.

Reference [19] presents a procedure for calibrating a hydraulic model using a genetic algorithm (GA). It is applied to a real-life network and it optimizes the settings of a throttle control valve at different timings for calibration. It is discussed a detailed case study, GA calibration model, methodology and results of calibrated models. The next step consists in identifying optimal sensor locations using a newly developed software tool named 'S-PLACE GA'. Its efficiency and effectiveness are debated.

Lee and Deninger [20] present a study describing a procedure for optimal positioning of monitoring stations for water quality control in water distribution networks. However, they do not approach the determination of roughness factors of the pipes, nor the relationship between nodal flows and diameters, which could be due to the verification of tube versus node interactions, through the friction head. In fact, they address the nodal demands and their interrelations, since they are a quality problem, where the distribution of volumes is the most important factor.

Reference [21] presents a Demand Coverage Index (DCI) based method. The optimization considers extended period unsteady hydraulics due to the change of nodal demands with time. The method is cast in a genetic algorithm framework for integration with the EPANET software and it is demonstrated by example applications. Results show that the set of optimal locations of monitoring stations obtained using the DCI method can represent the decision variables under multiple demand patterns better than other methods.

This work presents an alternative method for the identification of monitoring stations, called the characteristic nodes method (CNM). The method is applied to a water distribution network, presenting very satisfactory results. The process used in the calibration procedure is a reverse method, consisting of the association of a hydraulic simulator based on the TMA model with the Nelder-Mead optimizer algorithm, known as the hybrid model.

V. Sensitivity Analysis

Within the idea of having a limited number of monitoring stations, it becomes important to know what is the effect that the assumption of an incorrect roughness for each of the pipes will have in the resulting pressures or knowing which pipes most influence the set of nodes. This is called sensitivity analysis.

For this purpose, it is interesting to take values of dh/dC, which means the variation of nodal pressure in relation to a unit variation of the roughness coefficient, concerned to the Hazen-Williams formula. Thus, such derivatives are calculated numerically through a small increment in C. The system is simulated, and pressure changes are checked in the nodes of interest. It results in a sensitivity matrix, which is the structure formed by the values of dh/dC, referring to each node and each tube [22].

Reference [6] indicates the sensitivity analysis for the selection of monitoring points, seeking the determination of real values of roughness of the pipes. According to them, the importance of sensitivity matrices is, initially, to allow to evaluate whether small errors in the calibration of roughness can result in considerable errors in the flows and heads computed by the model. Therefore, these matrices are also important because they provide good indications about which points to monitor. They emphasize that if piezometric heads vary relatively with roughness coefficients, then the variation of these heads will minimally affect the coefficients. They also state that a node (or a pipe section) will not always present the same sensitivity to the roughness of different pipes, and it is therefore necessary to consider the sensitivity of each node (or pipe section) in relation to all roughness coefficients to be calibrated. They recommend that, for better calibration results, operations should be performed at night, when consumption can be practically ignored. They adopt that the number of monitored data is equal to the number of pipes to be calibrated.

VI. Proposition for Identification of Monitoring Stations

As seen, when the calculated pressure values are equal to those that were monitored (objective function equal to zero), the calculation roughness values, which led to the final pressures, do not always converge to the actual roughness values. Therefore, it is important to have a procedure for satisfactory identification (quantity and positioning) of monitoring points.

The alternative method adopted in the present work is to seek which nodes most influence the pipes, that is, which ones must necessarily be included, due to their high influence. This procedure will be called the characteristic nodes method (CNM).

Considering that, at that moment, the variables of attention are the pipes, it was proposed a scheme to verify which nodes that, through a unit variation of their pressure, have a considerable impact on the roughness of the pipes. Those would be the nodes that cannot be left out of the monitoring process, that is, the stations adopted as characteristics ones. It is a process very similar to the sensitivity analysis, however the inverse. Therefore, the verifications are operationalized by inversion of sensitivity analysis values, mathematically through the derived of roughness in relation to nodal pressure.

VII. Study Case

The method described was applied to a hydraulic network to verify its effectiveness. For this purpose, it is considered that the method will have been effective if, when the hybrid model convergence, i.e., equality between monitored pressures and calculated pressures, the estimated *C* roughness coefficient values (which led to such convergence) have approached the actual roughness coefficients as much as possible. The network to be calibrated is shown in Fig. 1, and its parameters are in the following tables.

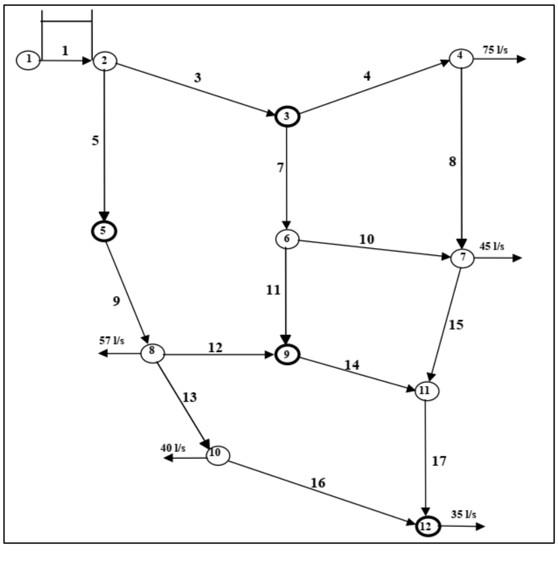

Figure 1. Hydraulic network to be calibrated.

TABLE I. Network Data

Pipe	N1	N2	L (m)	D (mm)	C
3	2	3	3000	500	100
4	3	4	1500	400	100
5	2	5	2500	400	100
7	3	6	1500	200	100
8	4	7	2200	300	90
9	5	8	1500	400	100
10	6	7	2200	500	100
11	6	9	2500	200	110
12	8	9	2700	200	100
13	8	10	2000	250	120
14	9	11	1700	200	100
15	7	11	1800	250	100
16	10	12	1000	200	100
17	11	12	1200	200	100

TABLE II. Reservoir Data

R1	N1	N2	Level (m)
1	1	2	100

TABLE III. Nodal Heads

Node	Head (mwc)
1	100.00
2	100.00
3	95.01
4	89.63
5	92.36
6	87.88
7	87.02
8	87.78
9	87.15
10	78.35
11	85.37
12	77.59

The sensitivity matrix was obtained numerically due to the lack of particular equations that relate the value of the head to the roughness coefficient, which would allow the analytical calculation of the derivatives. Arbitrating the "unit" variation of *C* as an increment of 10 units in its value, the pressure differences in the node obtained with the real *C* and with the altered *C* were verified, generating the dh/dC, noting that h represents the nodal pressure, *C* is the roughness coefficient of Hazen-Williams, and dh/dC is the rate of instantaneous variation of one in relation to another.

The values of dh/dC were considered in module to standardize positive and negative values, and multiplied by 100, to facilitate their manipulation.

After the analyses as described, the sensitivity matrix referring to the network in Figure 1 is shown in Table IV.

TABLE IV. SENSITIVITY MATRIX

	Node	3	4	5	6	7	8	9	10	11	12	∑	%
Pipe	P(real)	95.01	89.63	92.36	87.88	87.02	87.78	87.15	78.35	85.37	77.59	-	-
	P(ΔC3)	95.76	90.31	92.50	88.46	87.62	88.00	87.57	78.66	85.87	77.95	-	-
	$(dh/dC)_3$	75	68	14	58	60	22	42	31	50	36	456	19%
	P(ΔC4)	94.95	90.33	92.47	88.30	87.54	87.95	87.47	78.60	85.79	77.88	-	-
	$(dh/dC)_4$	6	70	11	42	52	17	32	25	42	29	326	13%
	P(ΔC5)	95.11	89.83	93.42	88.26	87.35	88.71	87.72	79.12	85.83	78.28	-	-
	$(dh/dC)_5$	10	20	106	38	33	93	57	77	46	69	549	23%
	P(ΔC7)	94.98	89.69	92.42	88.19	87.21	87.87	87.34	78.47	85.55	77.72	-	-
	$(dh/dC)_7$	3	6	6	31	19	9	19	12	18	13	136	6%
	P(ΔC8)	94.98	89.52	92.42	88.11	87.30	87.87	87.32	78.48	85.59	77.74	-	-
	$(dh/dC)_8$	3	11	6	23	28	9	17	13	22	15	147	6%
	P(ΔC9)	95.07	89.75	92.23	88.11	87.22	88.33	87.49	78.81	85.65	78.00	-	-
	$(dh/dC)_9$	6	12	13	23	20	55	34	46	28	41	278	11%
	P(ΔC10))	95.01	89.64	92.35	87.81	87.06	87.76	87.12	78.34	85.38	77.59	-	-
	$(dh/dC)_{10}$	0	1	1	7	4	2	3	1	1	0	20	1%
	P(ΔC11)	95.00	89.62	92.37	87.86	87.01	87.79	87.19	78.36	85.37	77.60	-	-
	$(dh/dC)_{11}$	1	1	1	2	1	1	4	1	0	1	13	0.5%
	P(ΔC12)	95.01	89.64	92.35	87.91	87.04	87.75	87.19	78.34	85.39	77.59	-	-
	$(dh/dC)_{12}$	0	1	1	3	2	3	4	1	2	0	17	0.5%
	P(ΔC13)	95.03	89.68	92.30	87.96	87.12	87.69	87.20	79.24	85.56	78.31	-	-
	$(dh/dC)_{13}$	2	5	6	8	10	9	5	89	19	72	225	9%
	P(ΔC14)	95.01	89.64	92.35	87.88	87.05	87.76	87.08	78.36	85.46	77.62	-	-
	$(dh/dC)_{14}$	0	1	1	0	3	2	7	1	9	3	27	1%
	P(ΔC15)	95.00	89.60	92.38	87.87	86.98	87.81	87.20	78.42	85.52	77.68	-	-
	$(dh/dC)_{15}$	1	3	2	1	4	3	5	7	15	9	50	2%
	P(ΔC16)	95.01	89.63	92.35	87.89	87.03	87.77	87.15	78.30	85.39	77.65	-	-
	$(dh/dC)_{16}$	0	0	1	1	1	1	0	5	2	6	17	0.5%
	P(ΔC17)	94.98	89.57	92.42	87.80	86.92	87.87	87.09	78.79	85.17	78.19	-	-
	$(dh/dC)_{17}$	3	6	6	8	1	9	6	44	20	60	163	7%

a. The $(dh/dC)_i$ value, where *i* is the pipe number, is given by: | P(ΔCi) – P(real) | x 100.

The most influential pipes were, in order of importance, 5, 3, 4, 9, 13, 17, 7 (and 8), 15, 10 (and 14) and 11 (and 12 and 16), since they led to a greater sum of nodal pressure variation considering a unit variation in their value (10 units in *C*, actually).

Then, according to this proposal, it will be a process of defining which points to monitor. Following the proposed scheme of most influential nodes or characteristic nodes (nodes that most affect the pipes), the values of the sensitivity matrix found are reversed (here called the matrix of characteristic nodes). This is presented in Table V.

Thus, it was considered that the nodes with the greatest influence on the pipes, that is, those that should be monitored, are those that presented the highest sum of values, along all pipes, being, in order of importance, respectively the nodes 3, 4, 5, 12, 6, 10 and so on. These were the six pipes used in the process of measurement of the accuracy of the method, as below. When the dh/dC values were zero, so that the computational calculations for their inversion did not fail, they were approximated to 0.5, considering the order of magnitude of the values present there.

In order to be able to assess whether the *C* values that made the calculated pressure equal to the monitored pressure were equivalent to the actual values of C, and if they were not, how much they differed, the CALIBRA application was used, as can be seen in Fig. 2.

The CALIBRA application is used in 3 modules. The first is the input of the network data, the second is the simulation step, providing the final values of nodal pressure (also provides the flows in the branches) and, finally, the calibration step. In the last module, the application uses a topology already defined, with the monitoring stations arbitrated by the method proposed here and with the pipes roughness to be adjusted to calculate the final values of C, so that the calculated pressure values meet those monitored. Thus, it is possible to verify whether this method was efficient in indicating such stations.

TABLE V. CHARACTERISTIC NODES MATRIX

Pipes	Node 3	Node 4	Node 5	Node 6	Node 7	Node 8	Node 9	Node 10	Node 11	Node 12
3	0.013	0.015	0.071	0.017	0.017	0.045	0.024	0.032	0.020	0.028
4	0.167	0.014	0.091	0.024	0.019	0.059	0.031	0.040	0.024	0.034
5	0.100	0.050	0.009	0.026	0.030	0.011	0.018	0.013	0.022	0.014
7	0.333	0.167	0.167	0.032	0.053	0.111	0.053	0.083	0.056	0.077
8	0.333	0.091	0.167	0.043	0.036	0.111	0.059	0.077	0.045	0.067
9	0.167	0.083	0.077	0.043	0.050	0.018	0.029	0.022	0.036	0.024
10	2.000	1.000	1.000	0.143	0.250	0.500	0.333	1.000	1.000	2.000
11	1.000	1.000	1.000	0.500	1.000	1.000	0.250	1.000	2.000	1.000
12	2.000	1.000	1.000	0.333	0.500	0.333	0.250	1.000	0.500	2.000
13	0.500	0.200	0.167	0.125	0.100	0.111	0.200	0.011	0.053	0.014
14	2.000	1.000	1.000	2.000	0.333	0.500	0.143	1.000	0.111	0.333
15	1.000	0.333	0.500	1.000	0.250	0.333	0.200	0.143	0.067	0.111
16	2.000	2.000	1.000	1.000	1.000	1.000	2.000	0.200	0.500	0.167
17	0.333	0.167	0.167	0.125	1.000	0.111	0.167	0.023	0.050	0.017
∑	11.947	7.120	6.415	5.413	4.638	4.244	3.756	4.644	4.483	5.886

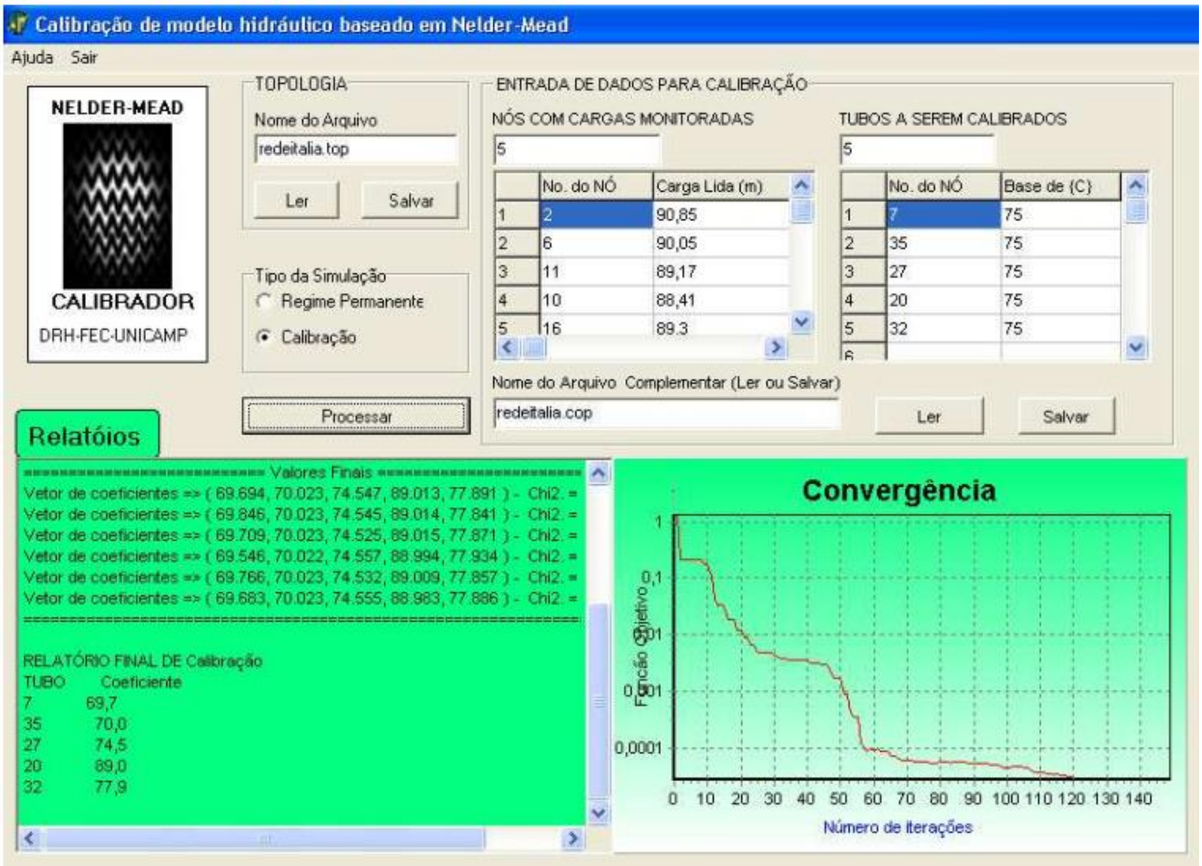

Figure 2. CALIBRA application interface.

VIII. RESULTS

Once the sensitivity and characteristic nodes matrices for the network presented were established, it was a question of adopting the most influential pipes and, from these, the monitoring stations, chosen by the CNM, for the purpose of verifying its accuracy. Once these parameters were defined, they were applied to the hybrid model, translated in the CALIBRA application, as described above, and the results were obtained, as illustrated in tables VI to X.

In these, it is possible to verify the percentage difference between the actual values of the roughness coefficient *C* and the values that this coefficient reached when the calculated pressures were equal to the measured pressures. It was established that the number of monitoring stations was always equal to the number of calibrated pipes, which were taken from 6 to 2, withdrawing the least influential of the stations, consequently, also the pipe of lower representativeness. As can be seen, the percentage differences were quite small.

TABLE VI. ROUGHNESS COEFFICIENT VALUES (FOR THE MONITORED NODES 3, 4, 5, 12, 6, 10)

	Pipe 5	Pipe 3	Pipe 4	Pipe 9	Pipe 13	Pipe 17
C_{real}	100	100	100	100	120	100
$C_{calibration}$	99.9	100.1	100.0	99.6	120.2	100.1
Difference	0.1%	0.1%	0%	0.4%	0.2%	0.1%

TABLE VII. ROUGHNESS COEFFICIENT VALUES (FOR THE MONITORED NODES 3, 4, 5, 12, 6)

	Pipe 5	Pipe 3	Pipe 4	Pipe 9	Pipe 13
C_{real}	100	100	100	100	120
$C_{calibration}$	100.0	100.1	100.0	99.6	120.3
Difference	0.1%	0.1%	0%	0.4%	0.3%

TABLE VIII. ROUGHNESS COEFFICIENT VALUES (FOR THE MONITORED NODES 3, 4, 5, 12)

	Pipe 5	Pipe 3	Pipe 4	Pipe 9
C_{real}	100	100	100	100
$C_{calibration}$	100.0	100.0	100.0	100.1
Difference	0%	0%	0%	0.1%

TABLE IX. ROUGHNESS COEFFICIENT VALUES (FOR THE MONITORED NODES 3, 4, 5)

	Pipe 5	Pipe 3	Pipe 4
C_{real}	100	100	100
$C_{calibration}$	100.0	100.0	100.0
Difference	0%	0%	0%

TABLE X. ROUGHNESS COEFFICIENT VALUES (FOR THE MONITORED NODES 3, 4)

	Pipe 5	Pipe 3
C_{real}	100	100
$C_{calibration}$	100.1	100.0
Difference	0.1%	0%

IX. CONCLUSIONS

The characteristic nodes method (CNM) proved to be quite efficient in the selection of pressure monitoring stations for the correct calibration of hydraulic networks by the hybrid model. This could be verified by the fact that, when the convergence between real pressures (monitored) and calculated pressures, the actual roughness values were approximately equal, if not totally, to the roughness values used in the calculation process.

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