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Procedia Engineering 186 (2017) 551 – 558

Procedia Engineering

www.elsevier.com/locate/procedia

XVIII International Conference on Water Distribution Systems Analysis, WDSA2016

Feasibility of mass balance approach to Water Distribution Network model calibration

Luigi Berardi*, Antonietta Simone, Daniele Laucelli, Orazio Giustolisi

Politecnico di Bari, Dept. of Civil Engineering and Architecture via Orabona n.4, 70125, Bari, Italy

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Abstract

The increase of real water losses in water distribution networks (WDNs) is worrisome for social community and water utilities. Nowadays, enhanced WDN hydraulic models allow simulating pressure-dependent background leakages, thus, being of direct relevance to support water loss reduction actions. Unfortunately, traditional calibration approaches rely on demand-driven analyses and do not account for additional parameters of the pressure-dependent background leakage models. This work proposes a novel framework for calibrating enhanced WDN models which permits to pursue mass-balance (matching of flow observations at water sources) by accounting for pressure-dependent water demand components and demand patterns. At the same time, energy balance (matching of pressure observations) allows to get the realistic prediction of all water demands and background leakages. The novel calibration strategy involves the simultaneous estimation of pipe hydraulic resistances, parameters of the background leakage model and relevant customer demand patterns. The feasibility of the strategy is demonstrated on a real WDN located in Southern Italy.

Peer-review under responsibility of the organizing committee of the XVIII International Conference on Water Distribution Systems

Keywords: Water distribution networks; WDN models; calibration; background leakages

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1. Introduction

Nowadays, leakages from water pipelines entail waste of water and energy resources and are a major issue in water distribution networks (WDNs) management, since they reduce system capacity under normal operating conditions and

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* Corresponding author. Tel.: +39-080-5963726; fax: +39-080-5963719.
E-mail address: luigi.berardi@poliba.it

Peer-review under responsibility of the organizing committee of the XVIII International Conference on Water Distribution Systems
doi:10.1016/j.proeng.2017.03.269

exacerbates possible water scarcity scenarios, e.g. due to socio-economic factors and/or climate changes. Besides, high rates of *background leakages*, representing the largest figure of annual water loss volume from WDN, are usually associated with increasing number of major pipe failures (i.e. *bursts*), which might cause service disruptions and third party damages. Accordingly, the effective management of WDNs for background leakage reduction is strategic for the social communities and water utilities.

In this context, WDN hydraulic models are crucial since they allow analysing the status of such systems in order to assess the impact of planning and management actions. Accordingly, the more accurate WDN hydraulic models, the more effective for supporting technical actions. The model calibration "consists of determining the physical and operational characteristics of an existing system and determining the data that when input to the computer model will yield realistic results" [1].

Traditionally, WDN models were mainly used to support the design of new water supply systems and/or to verify the WDN hydraulic capacity under some assigned service conditions (e.g. in order to verify sufficient pressure at hydrants for firefighting purposes). From such perspective, WDN model calibration mainly aimed at getting accurate prediction of pipe head-losses and the calibration "inverse problem" was originally formulated as the assessment of model parameters (i.e. pipe hydraulic resistances) that maximize the matching between pressure measured at sampling nodes and pressure values obtained from model run. Such approach exploited the classic demand-driven analysis (DDA) since the assigned service conditions were represented by nodal demands independent on current pressure status. A comprehensive literature review of the WDN model calibration methods based on such a traditional approach is reported in [2]. Unfortunately, all these methods completely neglected pressure-leakage relationship, thus making the resulting model not effective for supporting the management of existing WDNs.

Since the last decades of nineties, the main technical interest of water utilities moved from designing water supply systems *ex novo* to supporting management decisions on systems that were built right after the World War II and were progressively facing asset deterioration. In addition, the growing consideration of water and energy resources in recent years motivated the development of sustainable WDN operations in terms of environmental (i.e. carbon footprint), social and economic impact. This new technical context posed the challenge of more realistic hydraulic models that should overcome the limitations of classic WDN modelling, as mentioned in the special session "The Open Source Epanet project" at CCWI 2015 conference (www.water-system.org/ccwi2015). In fact, the WDN hydraulic models have to simulate both normal working conditions and pressure deficient scenarios that occur in real systems in consequence of increasing demands (e.g. due to socio-economic and climate changes), asset deterioration (e.g. increase of pipe hydraulic resistance due to ageing), system failures (e.g. pipe bursts) and/or background leakages (e.g. [3]).

Nowadays, a new generation of enhanced WDN models is available to perform pressure-driven analysis (PDA) (e.g. [4]) of all demand components including background leakages (e.g. [5][6]). Therefore, the calibration problem of the enhanced WDN models cannot be limited to estimating pipe hydraulic resistances, but should include the assessment of additional parameters, like those of the *background leakage* model.

In fact, differently from DDA where pipe flow rates are determined by fixed nodal demands, in PDA flow rates depends on current nodal pressure according to the pressure-dependent relationships used for modelling customer demand and *background leakages*. Consistently, the accurate prediction of head-losses along pipes depends on both pipe hydraulic resistances and nodal water demands that, in turns, depends on pressure. Consequently, the calibration of the enhanced WDN models should pursue both energy balance, i.e. the matching between measured and simulated nodal pressures, and mass-balance, i.e. matching between measured and simulated pipe flow rates due to the pressure-dependent demand components and demand patterns.

From such perspective, pressure measurements are used to get the realistic simulation of *background leakages and demand patterns*, besides providing information for estimating pipe hydraulic resistances; flow measurements allow driving the realistic prediction of water volumes circulating through the system. The latter aspect is actually of primary importance for understanding current system behaviour, identify areas with higher background leakages for allocating works and, eventually, use the calibrated model for prompt detection and identification of pipe bursts.

As reported for traditional calibration of hydraulic models [7], in order to increase the robustness of the calibration procedure and avoid a mere error-compensation, it is mandatory to consider a set of several independent steady-state observations of flow and pressure as well as the extended period simulation (EPS) of the network [8]. Therefore, the mass-balance calibration presented herein is based on the EPS using some time patterns of customer demands. Actually, the distribution of customers' demands in space and time is a major driver of WDN hydraulic status but such information reflect some prior assumptions based on the type of user/contracts (e.g. household, commercial, industrial, and so on). In addition, in some real contexts like the Mediterranean areas, the filling/emptying process of local water storages (i.e. private tanks feeding the customers' taps) shifts the peak of water demands (i.e. outflows from the system) from the peak of the assumed water requests. Recent works (e.g. [9][10][11]) proposed the calibration of for demand patters among the calibration variables, although such approaches did not consider pressure-dependent background leakages Actually, the identifiability of demand patterns permits to separate the contribution of customer demands from that of background leakages in the mass balance.

This work analyse the feasibility of a novel comprehensive framework for WDN model calibration based on mass-balance. It exploits a computationally effective and physically consistent multi-objective optimization strategy, where pipe hydraulic resistances, leakage model parameters and demand patterns are estimated simultaneously. The case study of a real network in Southern Italy is used to demonstrate the effectiveness of the methodology. It is worth to note that the mass-balance approach requires flow measurements data over time at least at water sources like tanks, reservoirs and pumping stations, and such data are normally collected by water utilities (e.g. for water balance purposes). Similarly, the records of pressure measurements at pump outlet nodes and water levels in tanks can be easily retrieved from existing metering apparatus and provide essential information on WDN pressure regime. Of course, pressure/flow measurements in other location (e.g. [7]) are desirable although the optimal design of sampling points is out of the scopes of this contribution.

2. Enhanced WDN hydraulic modelling

As mentioned above, in order to be effective to support planning and management of WDN, the hydraulic model should perform pressure driven analysis (PDA), incorporating pressure-dependent models for all water demand components, including *background leakages*.

Eq. (1) shows the general energy and mass balance equations in matrix form (e.g. [5]) underlying such enhanced WDN hydraulic model, over T steps extended period simulation.

$$\begin{bmatrix} \mathbf{A}_{pp}\left(\mathbf{K}\right)\mathbf{Q}_{p}\left(t\right)+\mathbf{A}_{pn}\mathbf{H}_{n}\left(t\right) & = & -\mathbf{A}_{p0}\mathbf{H}_{0}\left(t\right)+\mathbf{H}_{p}^{pump}\left(t\right) \\ \mathbf{A}_{np}\mathbf{Q}_{p}\left(t\right)-\left[\mathbf{d}_{n}^{leaks}\left(\mathbf{H}_{n},\boldsymbol{\beta},t\right)+\mathbf{d}_{n}\left(\mathbf{H}_{n},t\right)\right] & = & \mathbf{0}_{n} \end{bmatrix} \qquad \forall t=1,...,T \qquad (1)$$

In Eq. (1) $\mathbf{Q}_p(t)$: column vector of pipe flows; $\mathbf{H}_n(t)$: column vector of nodal heads; $\mathbf{H}_p^{pump}$ is the column vector of static heads of pump systems installed along pipes (if any) which can vary over time t in variable speed pumps; $\mathbf{H}_0$: nodes with known head value (e.g. reservoirs); $\mathbf{A}_{np}=\mathbf{A}^{\mathrm{T}}_{pn}$ and $\mathbf{A}_{p0}$: network topology incidence sub-matrices. $\mathbf{A}_{pp}(\mathbf{K})\mathbf{Q}_p(t)$: column vector of pipe head losses containing the terms related to internal head losses of pump systems, minor head losses and evenly distributed head losses; $\mathbf{K}$: vector of unit hydraulic resistance values K_k of pipes. $\mathbf{d}_n$ is the vector of all demand components [12] lumped at nodes (e.g. customer water demand, discharges from hydrants, filling of variable level tanks, etc.), except for *background leakages* that are explicitly reported in vector $\mathbf{d}_n^{leaks}$. Both $\mathbf{d}_n$ and $\mathbf{d}_n^{leaks}$ depend on nodal pressure (head) $\mathbf{H}_n(t)$ and on time t.

Background leakage outflows $\mathbf{d}_n^{leaks}$ are explicitly reported to depend on the leakage model parameters $\boldsymbol{\beta}$. Indeed, *background leakages* are intended as outflows running from small cracks, holes, deteriorated joints or fittings, occurring along pipes, thus including also unreported bursts. The *background leakages* can be modelled using various formulations, as for example in Giustolisi et al. [5] that used the Germanopoulos' model [13], while some recent works [14] proposed the formulation based on to the fixed and variable area discharge (FAVAD) approach [15] as completed by Van Zyl and Cassa [16]. In particular, the latter was proved to allow a more reliable model calibration since it is a linear expression with respect to two parameters $\beta_{1,k}$ and $\beta_{2,k}$ and was reported to be mainly independent from the average pressure head. Accordingly, each term of the background leakage vector $\mathbf{d}_n^{leaks}$ is computed as in Eq. (2).

$$\mathbf{d}_n^{leaks}\left(t\right)=\frac{1}{2}\left|\mathbf{A}_{np}\right|\mathbf{d}_p^{leaks}\left(t\right)=\frac{1}{2}\left|\mathbf{A}_{np}\right|\begin{bmatrix} d_1^{leaks}\left(P_{1,mean}\left(t\right)\right) \\ \ldots \\ d_k^{leaks}\left(P_{k,mean}\left(t\right)\right) \\ \ldots \\ d_{n_p}^{leaks}\left(P_{n_p,mean}\left(t\right)\right) \end{bmatrix} \tag{2}$$

$$d_k^{leaks}\left(P_{k,mean}\left(t\right)\right)=\begin{cases} \beta_{1,k}L_kP_{k,mean}^{0.5}\left(t\right)+\beta_{2,k}L_kP_{k,mean}^{1.5}\left(t\right) & P_{k,mean}\left(t\right)>0 \\ 0 & P_{k,mean}\left(t\right)\le 0 \end{cases} \tag{3}$$

where d_k^{leaks} is the background leakages outflow along the k^{th} pipe, $\boldsymbol{\beta}$ in Eq.(1) is a $2\times p$ matric containing for each row (pipe) the parameters $\beta_{1.k}$ and $\beta_{2,k}$. $P_{k,mean}(t)$ is the mean pressure along the each pipe at time step t and L_k is pipe length. The parameters $\beta_{1.k}$ and $\beta_{2,k}$ are the coefficients that characterize outflow from rigid leaks and variable-area leaks, respectively and are commonly assumed as invariant over time.

About $\mathbf{d}_n$, although it might include several expressions of pressure–dependent demand component, for the sake of presentation of the calibration methodology herein, it is assumed that $\mathbf{d}_n(\mathbf{H}_n, t)=\mathbf{d}_n^{cust}(\mathbf{H}_n, \mathbf{c}_n(t))$ that are the customer (human) controlled demand dependent nodal pressure (head) and on demand pattern values at time step t for each node. It is assumed herein that the elements of $\mathbf{d}_n^{hum}$ are represented by Wagners' model [17] in Eq. (4):

$$d_i^{cust}\left(t\right)=d_i^{cust}\left(P_i,t\right)=\begin{cases} c_i\left(t\right)d_{i,avg}^{req,cust} & P_i\left(t\right)\ge P_i^{ser} \\ c_i\left(t\right)d_{i,avg}^{req,cust}\dfrac{\sqrt{P_i\left(t\right)-P_i^{min}}}{\sqrt{P_i^{ser}-P_i^{min}}} & 0<P_i\left(t\right)<P_i^{ser} \qquad \forall t=1,\ldots,T \\ 0 & P_i^{min}\le 0 \end{cases} \tag{4}$$

where $c_i(t)$ is the demand pattern multiplier at time step t of the average water request $d_{i,avg}^{req,cust}$ at ith node; $P_i(t)$ is the current nodal pressure; P_i^{min} is the pressure to get any water; P_i^{ser} is the pressure to fully satisfy the water request. In Eq. (4) it is assumed that the pressure for correct service P_i^{ser} does not change over time, since it is related to the height of building and the water facilities lumped at ith node. It is to remark that, although during calibration the network is assumed to be never in deficit conditions, the modeling customer demands as in Eq. (3) is reported here since it is mode general and encompasses also the circumstance of sufficient pressure (i.e. falling into the DDA case).

3. Mass balance approach to WDN model calibration

The WDN model calibration problem is usually referred to as "inverse" problem (e.g. [8]). The enhanced WDN hydraulic model described above include the three main sets of parameters that need to be calibrated in order to get accurate representation of WDN hydraulic behaviour to support planning and management decisions:

- K_k: unit hydraulic resistance of pipes;
- $\beta_{1,k}$ and $\beta_{2,k}$: parameters of the background leakage model along of pipes;
- $c_i(t)$: multipliers of the average customer water request (i.e. demand patterns) at each node.

It can be argued that in real WDNs, each pipe should have its own values of K_k, $\beta_{1,k}$ and $\beta_{2,k}$, and for each node a dedicated demand pattern $c_i(t)$ (with $t=1,\ldots,T$) should be defined. This would mean to have, $n\times T+3\times p$ unknowns of the calibration problem, which makes the problem not-determined because pressure and flow observations are commonly available just on few nodes and pipes. Nonetheless, as for classic WDN model calibration, a commonly adopted strategy to reduce the number of unknowns is to group them according to some technical/hydraulic criteria.

Pipe calibration variables, K_k, $\beta_{1,k}$ and $\beta_{2,k}$ represents asset features of pipes that are independent from each other and can be reasonably assumed invariant over the operating cycle that is analyzed to perform the calibration. Nonetheless, pipes sharing similar asset characteristics as diameter, material and/or age are likely to show similar deterioration in terms of internal roughness, thus they can be designated with a unique value of K_k. Similarly, pipes can be grouped according to similar propensity to background leakages related to diameter, age, material and/or pressure regime leading to possible fatigue effects, thus showing the same values of $\beta_{1,k}$ and $\beta_{2,k}$.

Demand pattern (i.e. the set of $c_i(t)$) for each node is intended to reproduce a sequence of water requests that, in urban WDNs entails the statistical superimposition of several pulses representing individual opening of human controlled taps lumped at nodes. Accordingly, it is possible to use the same demand pattern for pipes showing a statistically similar water usage pattern (e.g. household). In urban WDN contexts, nodes belonging to the same demand pattern group are usually in the same neighborhood.

As reported in [18][19][20], the information on calibration variable that is available to water utility should be introduced in the solving procedure since it permits to restrain the effect of the uncertainties surrounding the calibration problem, driving towards realistic solutions. The calibration strategy proposed herein permits to introduce prior values of all calibration variables in different ways.

Prior values of unit hydraulic resistances K_k might descend from previous calibration procedure (e.g., using traditional DDA-based approach), or can be reasonably computed based on technical literature values or previous experience on similar pipes.

Prior values of the leakage model parameters ($\beta_{1,k}$ and $\beta_{2,k}$) cannot be obtained from DDA calibration, but can be assessed based on global leakage rate estimate that is usually available to water utilities.

Prior demand pattern values can be retrieved from billing data, from which all nodes with the same type of contract can be assumed to share the same patterns, as mentioned in previous section. Nonetheless, the present paper assumes no prior on *demand patterns*, since one of the main purpose here is to analyze the identifiability of correct demand patters allowed by the mass balance approach.

As for traditional WDN model calibration, this strategy pursues the minimization of the distance between observed and simulated flows and heads at p_s pipes with flow measurement and n_s nodes with pressure measurements. It is worth to remark that, differently from traditional WDN model calibration, the mass-balance approach requires flow observations at least at water storages (variable level tanks, reservoirs) and pumping stations. Actually, these measurements are commonly available at water utilities that collect such data for water balance purposes. Similarly, the records of pressure values at pump outlet and of water levels in tanks can be easily retrieved from existing apparatus and provide information on current pressure regime which affect background leakages.

The mass-balance calibration strategy is formulated as a multi-objective optimization which searches for optimal sets of N_K unit hydraulic resistance values (K_k), $2\times N_\beta$ parameters of the background leakage model ($\beta_{1,k}$ and $\beta_{2,k}$) and $T\times N_c$ multipliers ($c_i(t)$) for the N_c groups of pipes with the same expected pattern, that should simultaneously optimize the following objectives:

- minimize the distance from prior values of K_k, $\beta_{1,k}$ and $\beta_{2,k}$
- minimize the distance between simulated and observed pressure values at n_s sampling nodes
- minimize the distance between simulated and observed flow values at p_s flow observation pipes

4. Calibration of a real WDN model

This section demonstrates the mass-balance calibration strategy on a real WDN serving a town in Southern Italy with about 24000 inhabitants. The network layout is not reported herein for the sake of brevity, nonetheless it has to remark that the node elevation ranges between 302 m a.s.l. and 218 m a.s.l.; the highest point of the hill where the town is located is about 261 m a.s.l. The system is fed by gravity from the unique reservoir, which is about 4 km far from the distribution network, by two feeding lines having respectively nominal diameters of 500mm and 300mm. The range of elevations makes the highest urban area at low pressure in the peak demand hours at some nodes, while nodes at lower elevation can reach pressure above 40m. Actually, low pressure area does not suffer from insufficient water supply because most of the building are equipped with private storage systems that are connected to the WDN and fill-up during higher pressure times. Therefore, private pumping systems provide water to customers.

The water utility already developed a hydraulic model that reported 20 groups of homogeneous pipes, with relevant unit hydraulic resistances. Such information was taken as a prior for the calibration of K_k.

Based on previous analyses carried on by the water utility on this WDN, it was reported an exceptionally high background leakage rate of about 80% of total inlet volume mainly due to combined effect of oversized WDN and asset deterioration. Such information permitted to get a prior estimate of parameters $\beta_{1,k}$ and $\beta_{2,k}$ of the background leakage model in Eq. (3) which were unique for all pipes. The same 20 cohorts of unit hydraulic resistances have been used to group pipes with homogeneous expected parameters of the background leakage model.

Pressure observations were collected at nine nodes in the WDN. The only flow meter was available at reservoir outlet. All observations were collected simultaneously and data used for calibration span over 24 hours.

The water utility reported a unique demand pattern for all demand nodes in the WDN, consistently with the observation that household water consumption exceeds 85% of total nodal demands and, in this town, commercial and industrial activities are close to houses and are lumped in the same model nodes.

Both hydraulic simulation and the mass-balance based calibration is performed using the WDNetXL system [21], which is an integrated software platform for WDN analysis, planning and management, working in MS-Excel® environment. The WDN hydraulic model in WDNetXL integrates pressure-driven analysis of the WDN, including the simulation of background leakages, and the definition of several components of the demand in each node [6] with automatic analysis of WDN topology, as resulting, for example from automatic valve shutdowns. Although any control device is reported in the present case study, their functioning affect water mass circulation in the WDN, therefore the hydraulically consistent simulation of such devices is of primary importance to solve the calibration problem.

The calibration procedure returned 65 solutions, representing trade-offs among all objective functions reported in previous section. For the sake of brevity, only three of these solutions are summarized in Table 1 in terms of maximum and average absolute error on pressure at nodes and flow rate at tank outlet. In addition, the last three columns report the maximum and minimum correction factor of the prior values for parameters K_k, $\beta_{1,k}$ and $\beta_{2,k}$.

Table 1. Three solutions of the mass-balance calibration procedure.

Solution ID	Max Abs. Error on Observed Pressure [m]	Average Abs. Error Observed Pressure [m]	Max Abs. Error on Observed Flow [l/s]	Average Abs. Error on Observed Flow [l/s]	Corrections					
					K_k		$\beta_{1,k}$		$\beta_{2,k}$	
					min	*max*	*min*	*max*	*min*	*max*
6	4.38	1.73	2.99	1.36	0.38	2.00	0.28	1.43	0.32	1.67
27	5.25	2.01	2.19	0.72	0.20	3.33	0.29	3.33	0.40	1.61
47	5.92	2.33	1.85	0.81	0.60	1.67	0.13	5.88	0.40	2.56

Figure 1, shows the demand pattern provided by the water utility (i.e. “C”) and those obtained by the calibration procedure. It is to remark that the demand patterns provided by the water utility has not been used as prior during the calibration. Figure 1 shows that the demand patterns returned by the calibration procedure clearly follow the same trend as that reported by the water utility. Among the three solutions in Table 1, solution 47 is quite close to the pattern “C”, while solutions 6 an 27 shows lower minima (from 0.00 to 5.00. a.m.) and higher demand factors during the morning. These differences are consistent with the values reported in Table 1 in terms of global mass balance.

In fact, Solution 47 shows lower average and maximum errors on flow rates and larger errors on nodal pressure. Nonetheless, such mismatching on nodal pressure is somehow compensated by a larger range of corrections of the background leakage model parameters $\beta_{1,k}$ and $\beta_{2,k}$, consistently the relationship between pressure and parameters $\beta_{1,k}$ and $\beta_{2,k}$ in Eq. (3), while demand pattern is close to expected real system behavior.

In solution 27, the error on pressure is slightly lower and maximum error on flow rates increases. In this case, the range of corrections for $\beta_{1,k}$ and $\beta_{2,k}$ is narrower than solution 47 because this solution show larger distance between the estimated demand pattern and expected one “C”. Solution 6 with the lowest error on pressure observation shows the narrowest corrections for background leakage model parameters. Nonetheless, this solution results into the largest errors on flow rates, which are likely due to the highest drift from the expected demand pattern, as shown in Figure 1.

This proves that the mass balance calibration approach allows to separate the different components of the demand patters making clearly identifiable and hydraulically consistent the demand patters and returning returns realistic values of the background leakage model parameters.

Finally, Figure 2 shows the demand components (customers demand and background leakages) simulated over a 24 hours extended period simulation for the same WDN, assuming the demand pattern and the values of $\beta_{1,k}$, $\beta_{2,k}$ and K_k returned by the solution 47. It is worth nothing that, the combination between asset deterioration (as represented by the parameters of the background leakage model) and high pressure through the network, leads to a volume of background leakages largely exceeding the volume of water supplied to customers. This condition fully agrees with information available to the water utility for this WDN.

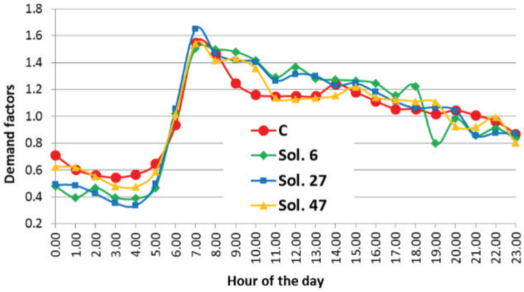
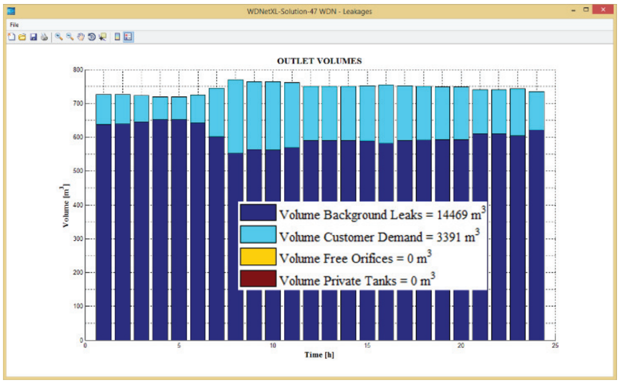


Fig. 1. Demand patterns of solutions 6, 27 and 47 of the calibration.



Volume Background Leaks = 14469 m^3
Volume Customer Demand = 3391 m^3
Volume Free Orifices = 0 m^3
Volume Private Tanks = 0 m^3

Fig. 2. Demand components simulated over 24 hours extended period simulation (solution n. 47).

5. Concluding remarks

Hydraulic models are used to support decisions on WDN operation, planning and management. Nowadays, enhanced WDN models incorporate pressure-dependent models of all water demand components including customer demands and background leakages. Such models permits to analyse the circulation of water volumes through the system, which is of primary importance for understand system behaviour and address possible actions. The calibration of such models asks for a hydraulically consistent approach where mass-balance, as represented by the matching of observed flow rates, has to be pursued together with energy balance, i.e. matching of nodal pressure. Indeed, differently from traditional approach, nodal pressure affects nodal demands and, therefore, pipe flowrates.

This contribution presents a comprehensive mass-balance calibration approach and demonstrates it on a real WDN. Consistently with the used hydraulic model, the calibration decision variables are the unit hydraulic resistances, the parameters of the background leakage model and the demand factor pattern. Although the approach is quite general, and to the FAVAD-based model for background leakages.

Results on real WDN show that the mass-balance approach permits to separate and identify customer demand patterns and background leakages. In those solutions showing closer customer demands pattern to the expected one, high errors on nodal pressure result into a wider range of the background leakage model parameters. *Vice versa*, larger differences in demand patterns, and high errors on pressure result into narrower range of the background leakage model parameters. Finally, solutions showing lower errors on nodal pressure and higher errors on flow rates are likely to show the largest drifts of demand patterns as well.

It is worth to remark that careful analysis of various calibration solutions based on such different indicators permits to get hydraulically consistent results, thus avoiding mere error compensation, and iteratively refine the calibration itself. Also, it is important to remark that in the analysed real WDN there are very high water losses because the network is oversized and deteriorated; in these circumstance a reliable model is further essential to support WDN management, thus its calibration is crucial to take effective decisions.

Acknowledgements

This research was partly funded by the project “Methodologies and tools for the sustainable management of urban water distribution networks in the Mediterranean area” funded by the “Future in Research” program – Apulian Region (Italy) and two projects of the National Relevant Scientific Research Programme PRIN-2012 (Italy): “Analysis tools for management of water losses in urban aqueducts” and “Tools and procedures for advanced and sustainable management of water distribution networks”.

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