2nd International Joint Conference on Water Distribution
Systems Analysis & Computing and Control in the Water Industry
Valencia (Spain), 18-22 July 2022
doi: https://doi.org/10.4995/WDSA-CCWI2022.2022.14770

MASS BALANCE CALIBRATION OF WATER DISTRIBUTION NETWORKS: APPLICATION TO A REAL CASE STUDY

Orazio Giustolisi[1], Francesco Ciliberti[2], Daniele Laucelli[3] and Luigi Berardi[4]

[1,3]Department of Civil, Environmental, Land, Building Engineering and Chemistry, Technical University of Bari, Bari (Italy)
[2,4] Department of Engineering and Geology, University "G. D'Annunzio" of Chieti-Pescara, Pescara (Italy)

[1] *orazio.giustolisi@poliba.it*, [2] *francesco.ciliberti@unich.it*, [3] *danielebiagio.laucelli@poliba.i*,
[4] *luigi.berardi@unich.it*

Abstract

Calibration of Water Distribution Networks (WDN) hydraulic models is mandatory to effectively support their analysis and management. As such, it should not be intended as the mere matching between model outputs and filed data but, rather, as a tool to understand WDN behavior under several different hydraulic functioning scenarios. The latest advanced hydraulic models encompass a phenomenological representation of the physical behavior of based on pressure-driven analysis. From such perspective, the problem variables include the parameters of the leakage model, the observable demand patterns and the average values changing day by day, as well as pipe hydraulic resistances, especially of the main water paths feeding the system. According to global mass-balance, the total water inflow recorded at source point (i.e., tanks, reservoirs, pumps) can be used to separate the stochastic component of water outflow, i.e., consumers' demands, from the deterministic component, i.e., pressure-dependent leakages at single pipe level.

This work demonstrates the innovative mass-balance paradigm applied for the calibration of few sub-networks of a large real WDN, which uses measurements collected in five characteristic days including summer, winter, holidays and working days. The resulting model allows a more robust prediction of the real system physical behavior and provide a reliable basis to support several design and management activities.

Keywords
WDN hydraulic model, calibration, leakages, demand patterns.

1 INTRODUCTION

Hydraulic models of Water Distribution Networks (WDN) are known to provide a methodological tool to support various asset planning and management tasks, as confirmed by the evolution of WDN hydraulic models of the last decades. Indeed, WDN models were initially conceived to support the design of new WDN, allowing to verify adequate pressure at delivery points, i.e., nodes of the model, under assigned demand and hydraulic capacity, i.e., pipe diameters of the sizing solution. Accordingly, the hydraulic modelling software (e.g., EPANET2, [1]) were built upon the assumption of fixed water outflows, i.e., demand-driven analysis (DDA). These models allowed WDN verification under both normal and abnormal water demand scenarios (e.g., firefighting).

Later, the increase in WDN deterioration and consequent leakage rates, motivated the introduction pressure-driven analysis (PDA) [2] and the conceptual basis through the definition of pressure-demand relationship for all types of indoor and outdoor components of demands, consistently with the Torricelli law [3]. The mostly adopted pressure-dependent function of customer demand resorted to Wagner's model [4], while pressure-dependent relationship for leakages was introduced in the eighties (e.g. [5]) and integrated into the PDA solving algorithm more than one decade ago [6] allowing the representation of leakages at pipe level depending on average pressure and deterioration.

Nowadays, WDN hydraulic models are used to support various asset management tasks including leakage reduction, pressure control, optimal design of District metering Areas (DMA), or sustainable pump operation. In order to support such tasks, the WDN hydraulic models have to provide a phenomenological representation of WDN, meaning that they should capture the emerging hydraulic behaviour of the network, which can be changed by proper management actions, e.g., installing pressure control devices (e.g. [7][8]), modifying water paths through district metering areas (e.g. [9] [10]) or implementing pipeline rehabilitation. This motivated the development of advanced WDN hydraulic models, like that used in this work, aimed at including many elements that are of direct relevance to support asset management and planning.

Such evolution in WDN modelling purposes also motivated some change in model calibration approach. Since the earliest contributions in this area, WDN model calibration was reported as the process of determining model parameters that will yield a reasonable match between measured and predicted pressures and flows in the network [11]. Accordingly, the calibration of DDA models took pipe hydraulic resistance as the main calibration variable aimed at maximizing the matching between simulated and measured pressure at some nodes (e.g. [12][13][14]). This framework emphasized the role of energy balance equations along pipes, while the mass balance, i.e., matching observed and simulated pipe flows over time, was used to adjust fixed nodal demands only, possibly including leakages patterns as additional fixed outflows. Recent works (e.g. [15][16][17]) included the calibration of demand patters, although they did not consider pressure-dependent background leakages.

The introduction of PDA motivated novel approaches to WDN model calibration since additional parameters of pressure-demand model components were introduced, beside pipe hydraulic resistance and water requests. In mode details, accounting for the leakage model in PDA requires the calibration of parameters representing leakage propensity. [18] reported that defining multiple groups of pipes that have different leakage propensity might provide accurate representation of leakages in WDN models. Nonetheless, as leakages depend on pressure and affect the distribution of water flows through the network, this asks for detailed monitoring, which is not always available, especially in those WDN which are in the process of installing meters and must use the hydraulic model to drive the designing of monitoring systems.

A novel approach to calibrate advanced WDN models was reported in [19] and inspired this contribution. It was based on the observation that time series of WDN water inflow equals the superimposition of two types of components of WDN water outflows, which can be referred to as *stochastic* and *deterministic*. *Stochastic* demand components refer to water requests from consumers, which changes day by day based on socio-economic or seasonal factors, i.e., working days, holidays, winter or summer. *Deterministic* demand components are directly related to asset conditions and pressure regime, i.e., pressure-dependent leakages. The variability of water requests of consumers over time (i.e., demand patterns) affect the WDN hydraulic status including pressures that, in turn, determine leakages. In PDA advanced models such variables should match energy and mass balance equations.

Using such paradigm [20] demonstrated that water flow measurements provide more effective information than pressure measurements for determining the distribution of leakages through the network. They also reported a strategy to assign different leakage model parameters to different pipes based on statistical model of failure propensity, consistently with the observation that the rate of pipe breaks increases with leakage rate (e.g., 21).

This contribution reports the application of WDN model calibration approach exploiting mass-balance, i.e. separating *stochastic* and *deterministic* demand components, on a real large WDN. The calibration of such WDN was part of a real procedure for planning district monitoring areas (DMA) integrated with leakage control actions, therefore it had to account for real constraints and uncertainties on available information and had to provide robust results to support next design activities. The implementation on such a real context allows to demonstrate the importance of some aspects which are usually neglected in classical WDN model calibration procedures: the existence of different WDN hydraulic status in different days; the change of leakage outflow over different days in consequence of change of pressure regimes; the actual observability of consumers' demand patters based on available measurements; the handling of unreducible uncertainties on actual status of some devices consistently with the intended model use.

2 REMARKS ON ENHANCED WDN HYDRAULIC MODELLING

This section briefly recalls the main features of enhanced WDN hydraulic model that is used herein to support the analysis and planning of works [22]. This is functional to identify the main variables to be calibrated and discuss some aspects of direct relevance in the real case applications.

It is worth to recall that the main assumption of WDN hydraulic modelling for planning purposes is the steady-state simulation conditions. This means that in each time interval ΔT, over an operating cycle (e.g., 24 hours), unsteady conditions are completely neglected and are not described in model equations. The choice of ΔT, e.g., 15, 30 or 60 minutes, depends on the peculiar modelling purpose (e.g. [23]), the variability of water demand patterns and the size of the network. During each ΔT water demands are assumed as stationary ([24][3]), i.e., with constant mean, and the filling/emptying process of water tanks is assumed as slow ([24]). On these premises, the mass balance and energy balance equations behind the enhanced hydraulic model can be written in matrix form (Giustolisi, 2020):

$$\begin{cases} \mathbf{A}_{pp}(t)\mathbf{Q}_p(t) + \mathbf{A}_{pn}\mathbf{H}_n(t) & = & -\mathbf{A}_{p0}\mathbf{H}_0(t) \\ \mathbf{A}_{np}\mathbf{Q}_p(t) - \dfrac{\mathbf{V}_n(t,\mathbf{H}_n(t))}{\Delta T} & = & \mathbf{0}_n \end{cases} \tag{1}$$

where p and n relate to the number of pipes and nodes (unknown heads), while the subscript "0" refers to the number of reservoirs (known heads). $\mathbf{Q}_p$, $\mathbf{H}_n$ and $\mathbf{H}_0$ are the column vectors of pipe flow rates, nodal heads and known nodal heads, respectively. $\mathbf{A}_{pn}$, $\mathbf{A}_{np}$ and $\mathbf{A}_{p0}$ are topological incidence sub-matrices of the general topological matrix, link-node, of the network. $\mathbf{A}_{pp}(t)\mathbf{Q}_p(t)$ is the column vector of pipe head losses containing terms related to internal head losses of pump systems, if any, minor head losses and evenly distributed head losses, i.e., depending on pipe hydraulic resistance parameters.

$\mathbf{V}_n$ is the column vector of volume outflows during a time interval ΔT lumped at nodes. The following equations reports the demand components that are included in $\mathbf{V}_n$, all dependent on pressure status ($\mathbf{H}_n$) and varying at each time step (t).

$$\begin{aligned} \mathbf{V}_n(t,\mathbf{H}_n(t)) = {} & \mathbf{V}_n^{cons}(t,\mathbf{H}_n(t)) + \mathbf{V}_n^{priv-tank}(t,\mathbf{H}_n(t)) + \\ & + \mathbf{V}_n^{orif}(t,\mathbf{H}_n(t)) + \mathbf{V}_n^{tank}(t,\mathbf{H}_n(t)) + \mathbf{V}_n^{leak}(t,\mathbf{H}_n(t)) \end{aligned} \tag{2}$$

$\mathbf{V}_n^{cons}(t, \mathbf{H}_n(t))$ is the water demand supplied to consumers directly connected to the water network which are computed using Wagner's model in pressure-deficient conditions, otherwise it equals the *stochastic* water requests, changing day by day. $\mathbf{V}_n^{priv\text{-}tank}(t, \mathbf{H}_n(t))$ represents the volume of water feeding private storage tanks in ΔT, which are commonly installed in many areas worldwide, including that of the real WDN [26]. $\mathbf{V}_n^{orif}(t, \mathbf{H}_n(t))$ is the water volume from uncontrolled free orifices, e.g. hydrants.

$\mathbf{V}_n^{leak}(t, \mathbf{H}_n(t))$ represents leakage volume, which is computed at single pipe level. It is worth to remark that $\mathbf{V}_n^{leak}$ in a WDN hydraulic model used to support asset management refers to background leakages and outflows from undetected/unreported pipe bursts. Such leakages are known also as *volumetric leakages* since they entail the major volumes of lost water at annual scale. Although the used model is able to include model formulations according to the FAVAD concept (e.g. [27]) and Gemanopoulos [5], the latter is report herein:

$$\frac{V_k^{leak}(t)}{\Delta T} = \begin{cases} L_k \beta_k P_{k,avg}^{\alpha_k}(t) & if \;\; P_{k,avg}(t) > 0 \\ 0 & if \;\; P_{k,avg}(t) \leq 0 \end{cases} \tag{2}$$

V_k represents distributed volumetric leakage volume in t along the kth pipe; L_k and $P_{k,avg}$ are the length and average pressure of that pipe; β_k is a pipe deterioration parameter and α_k is an exponent which can be assumed as 1, as reported in [23]. Half of V_k is then assigned to both nodes of the pipe in order to solve hydraulic equations in model (1). Assuming deterioration parameter at pipe level is useful for calibration purposes since it allows assigning values of β_k based on prior insight on leakage propensity (es in [20]).

3 MASS BALANCE APPROACH TO WDN MODEL CALIBRATION

The following figure depicts the separation of water demand components which is behind the mass-balance approach to WDN model calibration. Without impairing the general validity of the description, let's assume a WDN fed by one water "source" only (i.e., reservoir, tank or pump). The leftmost diagram shows in red the pattern of inlet water volumes recorded from the water "source", which can be thought as the superposition of *deterministic* volumetric leakages, depending on deterioration of pipes and pressure, and *stochastic* consumers' water demands.

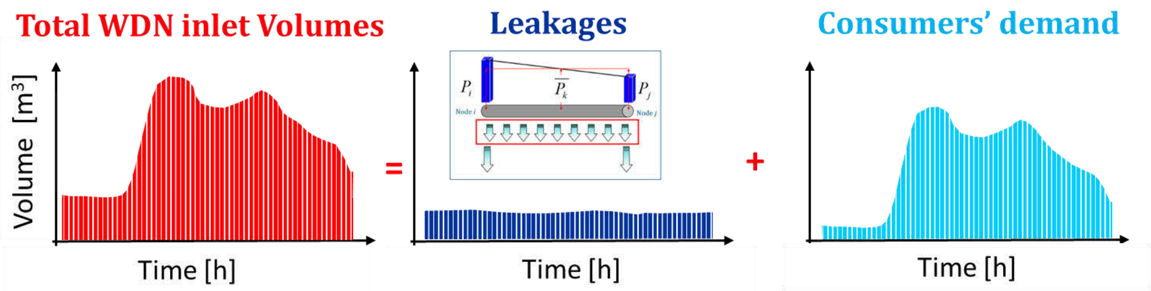

Figure 1. Separation of water demand components in mass-balance approach for WDN model calibration

The two components of water outflows should be in equilibrium with both global water inflow and the distribution of pressures in the network, which depends on flows circulating along pipes including both water supplied to consumers and leakages.

This approach gives rise to some remarks which are relevant while calibrating WDN hydraulic models to support asset management and planning actions.

The variables of the WDN model calibration problem are the deterioration parameters β_k, the hydraulic resistances of pipes, and the patterns of consumers' demand. The first two parameters deal with asset features, i.e., propensity to leak and deterioration; therefore, they can be assumed as invariant over multiple days.

About pipe deterioration parameters β_k, [20] used a methodology to assign different propensity to leak to different pipes. It was based on the using failure propensity models that can be borrowed from literature or developed *ad hoc* using data-modelling or statistical analyses on past pipe failure data. Such methodology was also adopted for the real case described herein.

The detailed calibration of hydraulic resistances at single pipe level requires flow and pressure measurements that usually are not available in real contexts. In addition, the vast majority of pipes in urban WDN represents the looped portion of the system. For these pipes multiple alternative water paths exists whose identification is not easy and make non unique the assessment of hydraulic resistance of these pipes base on limited number of flow/pressure measurements. Conversely, there are few pipes, e.g., those feeding the main distribution network from water sources. Such pipe can be longer than others (up do few kilometres) and carry larger discharges; therefore, assessing their hydraulic resistance values is of primary importance since they strongly affect the pressure regime in the entire system.

The calibration procedure adopted herein allows the assessment of hydraulic resistances of both types of pipes, starting from some prior values got from technical literature. The user can decide to calibrate the most relevant pipeline, groups of similar pipes or none of theme, assuming that prior values are reliable enough.

About the patterns of consumers' demand, it is known to change day by day and affect pressure regime, thus resulting into change of *volumetric leakages* over different days.

This confirms the findings of [12][28]: in order to avoid a mere error-compensation process and improve the robustness of model calibration, 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. Using sets of multiple operating cycles corresponding to working day and holidays in different seasons or even abnormal consumption days (e.g., New Year's Eve) allows more robust estimation of asset variables which are supposed to be invariant. This, in turn, increases the accuracy of identified consumers' demand pattern for each day.

The mass-balance approach also suggests that a unique demand pattern can be identified for each observable portion of the network (e.g., DMA), i.e. where al least inflow measurements are available at the boundaries of that network portion allowing mass balance estimate. Assuming demand patterns defined a priori (e.g., households, industrial, business, etc.) might introduce a strong bias for the identification of consistent demand patterns, deterioration parameters and hydraulic resistances. Prior information on demand patterns in some DMAs or in single consumers should be substantiated by detailed flow measurements.

It can be noted that the mass-balance calibration approach is quite flexible to exploit as much information as possible, while preserving the physical consistency of results to allow a robust phenomenological representation of WDN hydraulics. The main information required comes from inflow data and average consumption data (e.g., based on billing database). Information on pressure regime is useful to improve estimate of leakage model parameters. Nonetheless, it was demonstrated that changes in β_k, consistently with global mass balance, only change the distribution of leakages among pipes with negligible changes in pressure values. Pressure and flow information are both useful to calibrate the hydraulic resistance for the main feeding pipelines, while values borrowed from technical literature of pipe hydraulic resistances usually allow a reliable description of the distribution (looped) part of the system.

4 WDN MODEL CALIBRATION IN A REAL WDN

The mass-balance approach discussed above was applied on a real WDN in a large city in southern Italy. It was part of a larger procedure for asset management activities aiming at DMA design and pressure control for leakage reduction, with possible improvements of system hydraulic functioning.

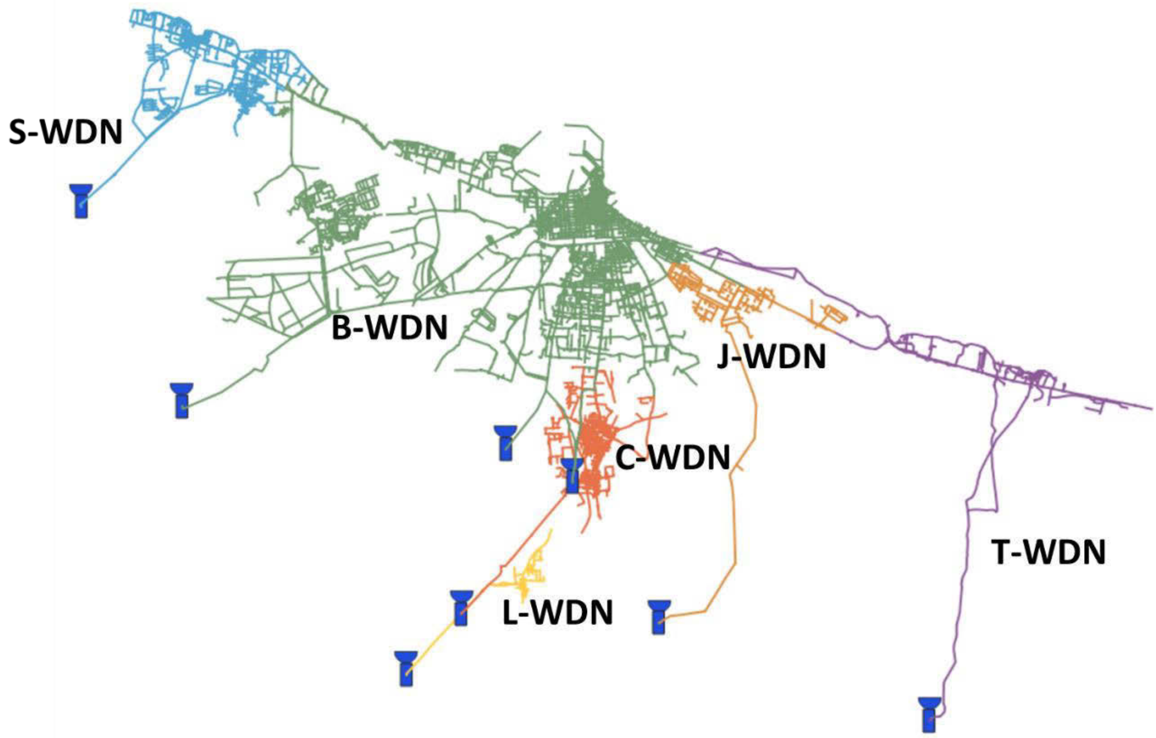

Figure 2. Plot of the real WDN and sub-networks

Table 1. Data of WD hydraulic model of each subnetwork

Sub-network	# Reservoirs	Length [km]	#Pipes	#Nodes	Control valves
T-WDN	1	52.71	350	325	1
J-WDN	1	43.27	358	332	2
L-WDN	1	12.87	169	144	-
S-WDN	1	86.59	1344	1181	-
C-WDN	1	75.82	1144	1007	1
B-WDN	3	424.33	5691	4783	3
Total	8	695.59	9056	7772	7

The WDN is composed of six subnetworks fed by eight reservoirs; the total length of pipeline is about 700km, with 7 pressure reduction valves. The system also includes about 80 partially closed valves (i.e., introducing minor losses) and about 150 closed gates. Figure 2 shows with different colours the six subnetworks and Table 1 summarizes key data for each WDN hydraulic model.

The mass-balance approach was used for calibrating the hydraulic model of each subsystem separately, using inflow data monitored from each reservoir and some pressure data in few monitoring points. It is worth noting to emphasize that mass balance paradigm requires synchronous data (i.e., data collected at all available meters in the same days), and average consumption of the same year. In this case, water consumption and monitored data at flow/pressure meters, along with information on settings of control valves referred to 2019.

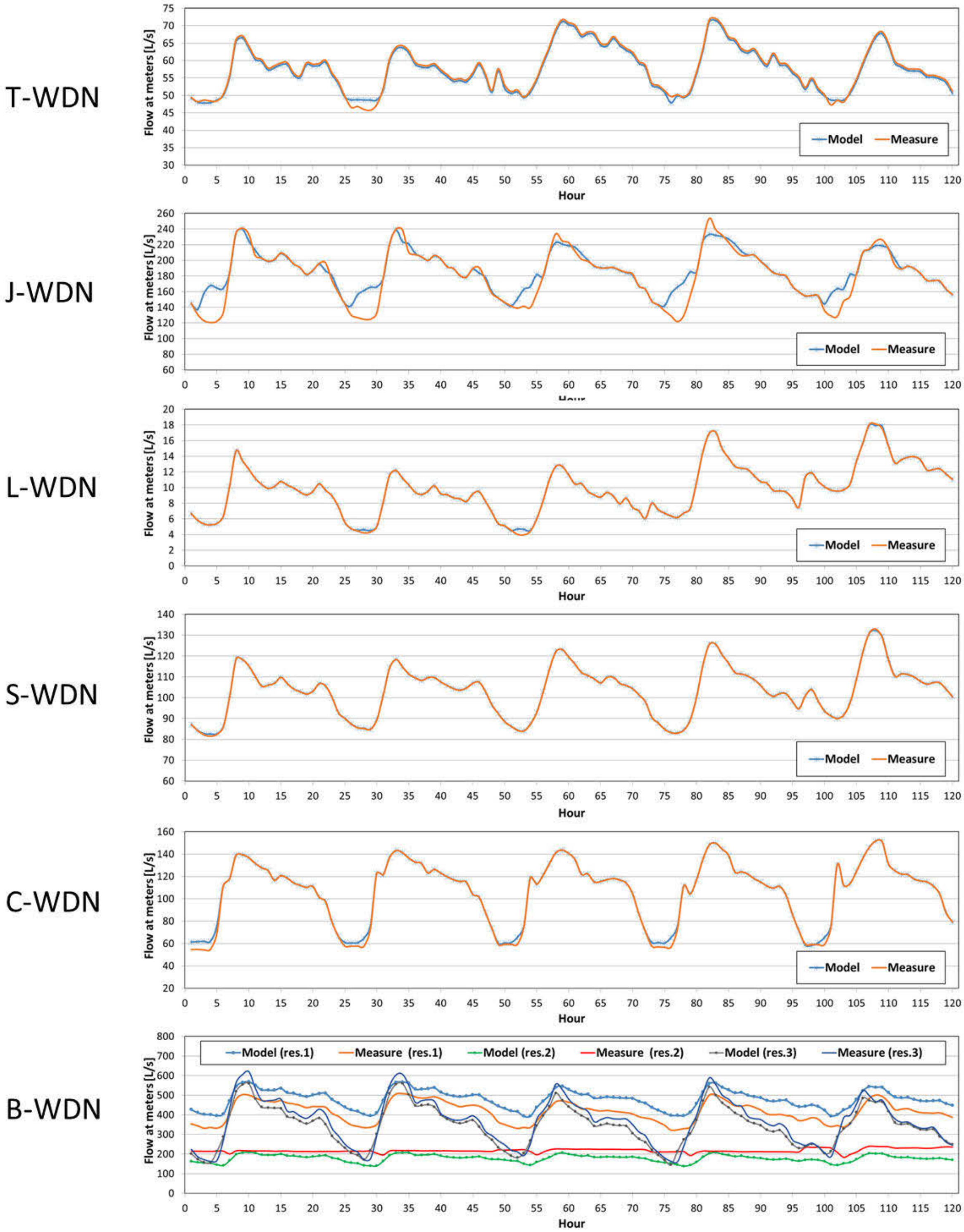

Figure 3. Calibration results: measured vs. model inflow data

For each subsystems the calibration was performed on five days (i.e., 120 timesteps of 1 hour each) representing week and weekend days during summer and winter, also including the 1st of January, representing an unusual pattern of consumptions. As each subnetwork was composed by one monitored “district”, only one demand pattern can be observed and identified in each model.

Figure 3 reports the results of calibration in each model, comparing measured data and model output at flow meters. It can be noted that in all sublots data follows the same trend and in the majority of time step data almost overlap. This does not happen in few time intervals, mainly during night, because of some unknown/unreported controls of hydraulic devices or unpredictable water usage. In the case of the biggest B-WDN, which is fed by three reservoirs, there is a sort of compensation effect between underestimates and overestimates of model flows compared with observed flows. This mismatching is mainly related to unreducible uncertainties about the actual status of many valves not yes reported in the model as declared by the water utility. This is a typical scenario in real contexts where a detailed monitoring system in still at early stages. Nonetheless, the calibration procedure pursued the global mass-balance at every simulation time step.

Figure 4 shows the unique demand patterns identified in each WDN model, while Figure 5 shows the patterns of linear leakage indicator (m^3/km/day), M1a in Italian regulation [29]. It can be noted that identified demand patterns changes over different hours of the day in consequence of peculiar socio-economic factors. These patterns determine changes in pressure and leakages, as demonstrated by the variability of the linear leakage indicator M1a.

Also noteworthy is that some spikes are identified in demand patterns for J-WDN. This happens since leakages changes in consequence of pressure control (by time) performed by a pressure reduction valve ns mass-balance modify the demand pattern to match the total inflow recorded. The unexpected behaviour identified in J-WDN, in conjunction with the exceptionally high linear leakage indicator (i.e., about 138 m^3/km/day) unveiled that either all pipes of this small network are highly deteriorated or there are major unreported leaks in few pipes that need to be detected. From such perspective, the mass-balance calibration helped in *reverse engineering*, i.e., suggesting some feasible explanations to unexpected results which can improve the knowledge of the real system.

Figure 6 explicitly reports the separation of total inlet volume into leakage and consumers' demand components across the five days. It can be noted that leakage volume changes across different days, although its variation is lower than changes in consumers' demand. This happens because such systems are usually oversized, resulting into small changes in average daily pressure.

Finally, next figures show the results of model calibration in terms of average pressure at nodes (Figure 7) and linear leakage index M1a (Figure 8) at single piper level. Such plots confirms that pipes under the same average pressure might have different propensity to leak, due to many factors including age, number of connections to private properties and diameters, as represented by the calibrated parameter β_k. This information is of primary importance to drive leakage reduction actions like, for example, selecting pipes for rehabilitation works without using the information of pipe age only.

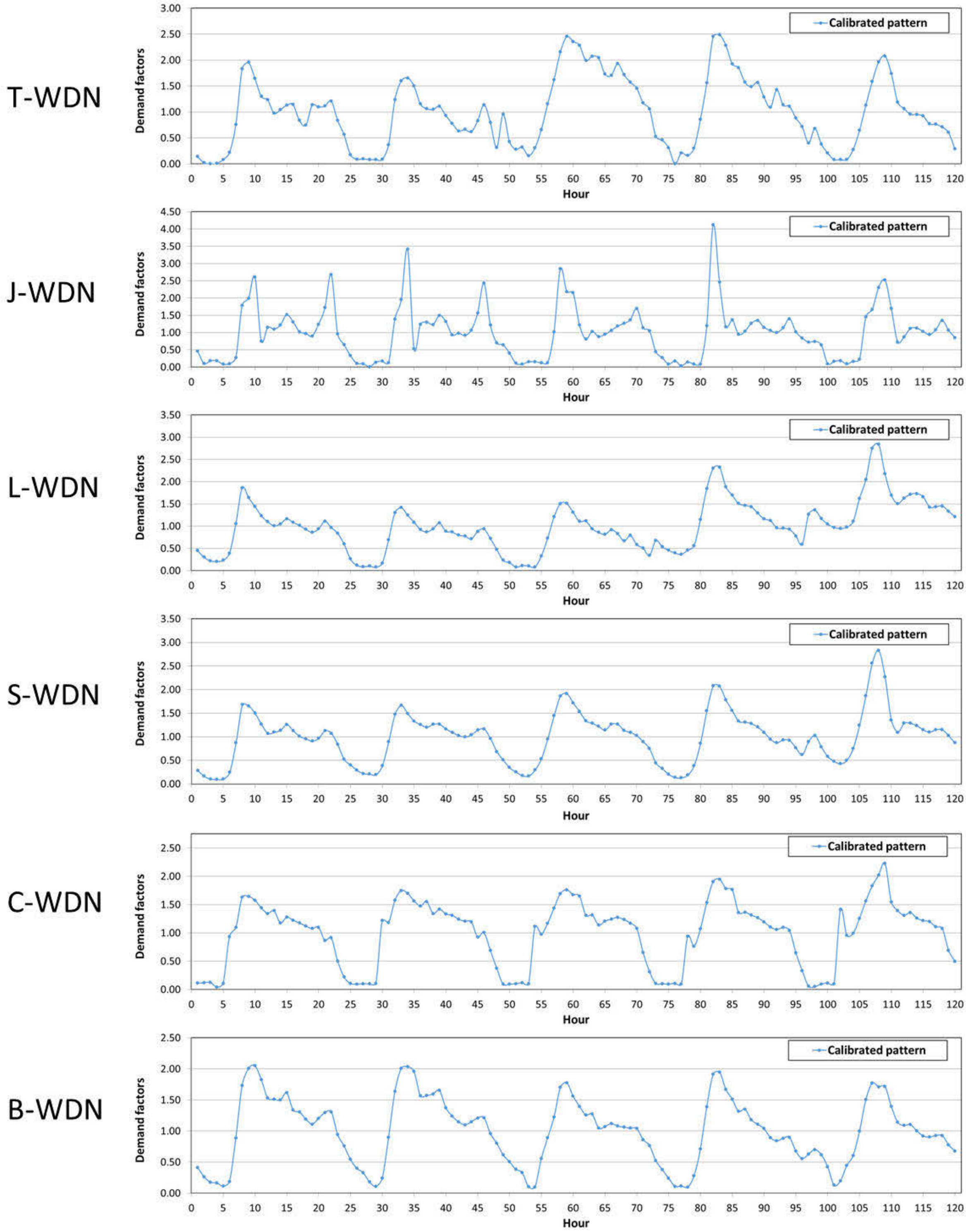

Figure 4. Calibration results: identified consumers' demand patterns

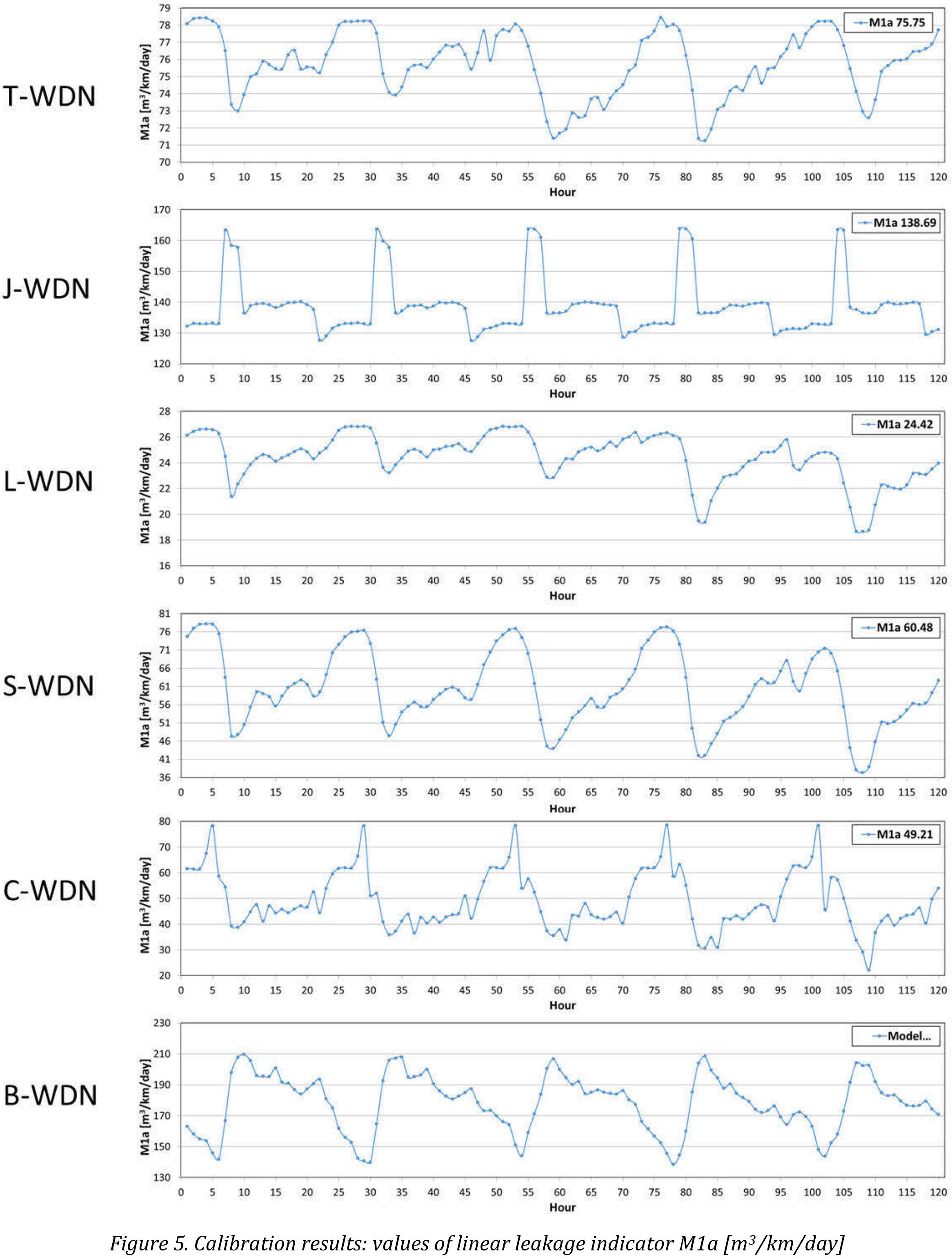

Figure 5. Calibration results: values of linear leakage indicator M1a [m³/km/day]

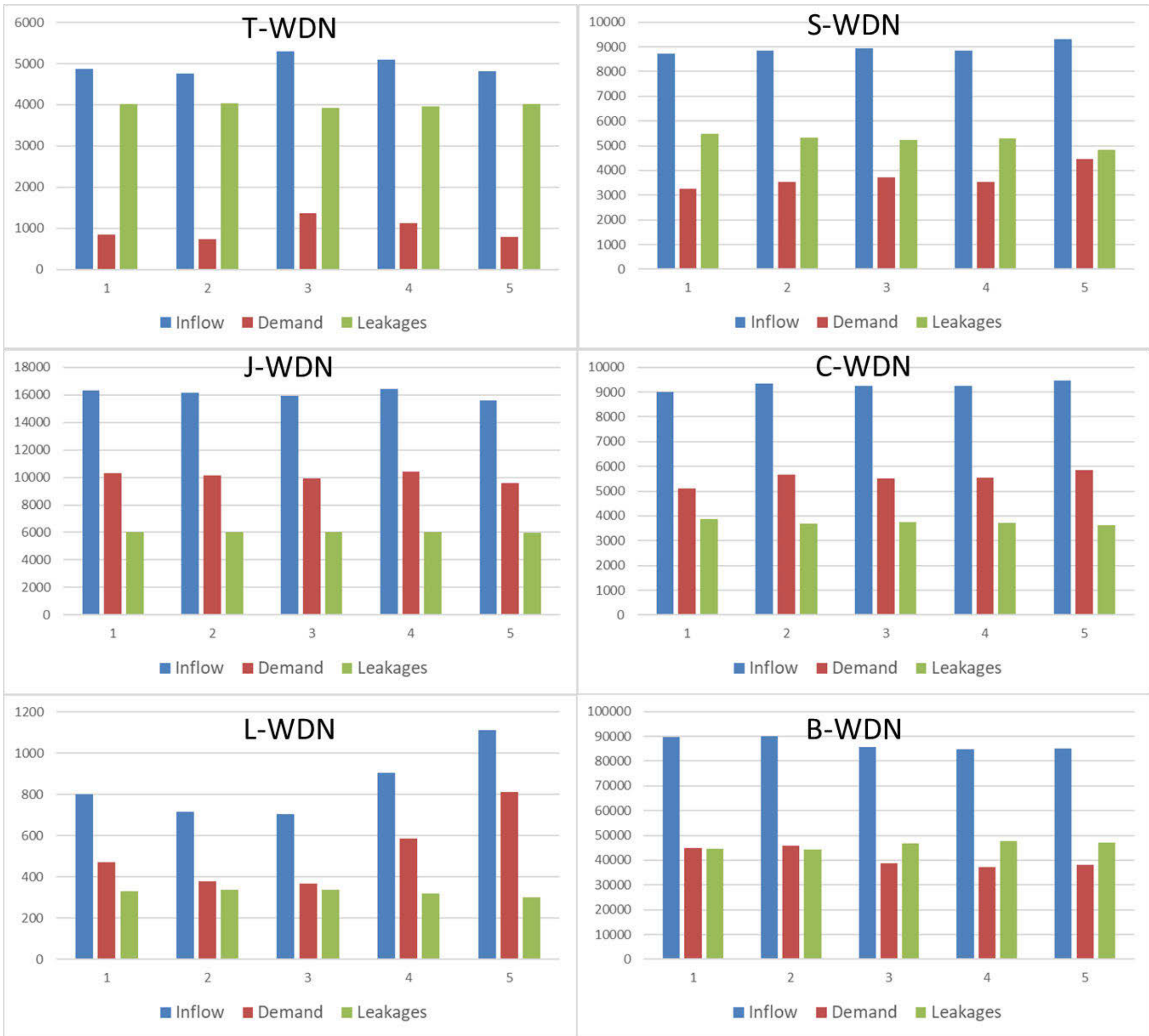

Figure 6. Calibration results: total inlet volume, volumetric leakages and consumers' demand over five operating cycles

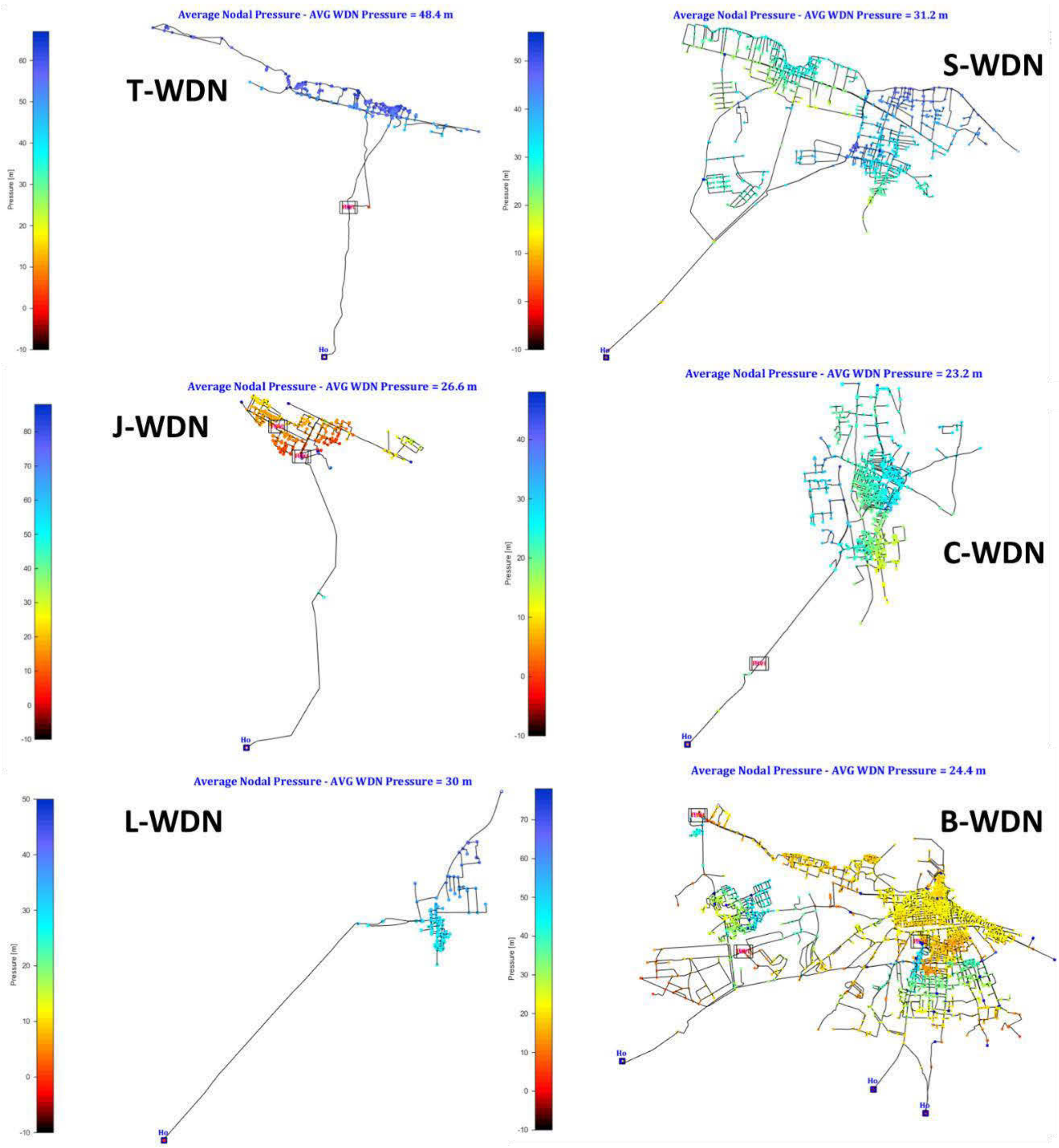

Figure 7. Calibration results: average pressure status at WDN model nodes

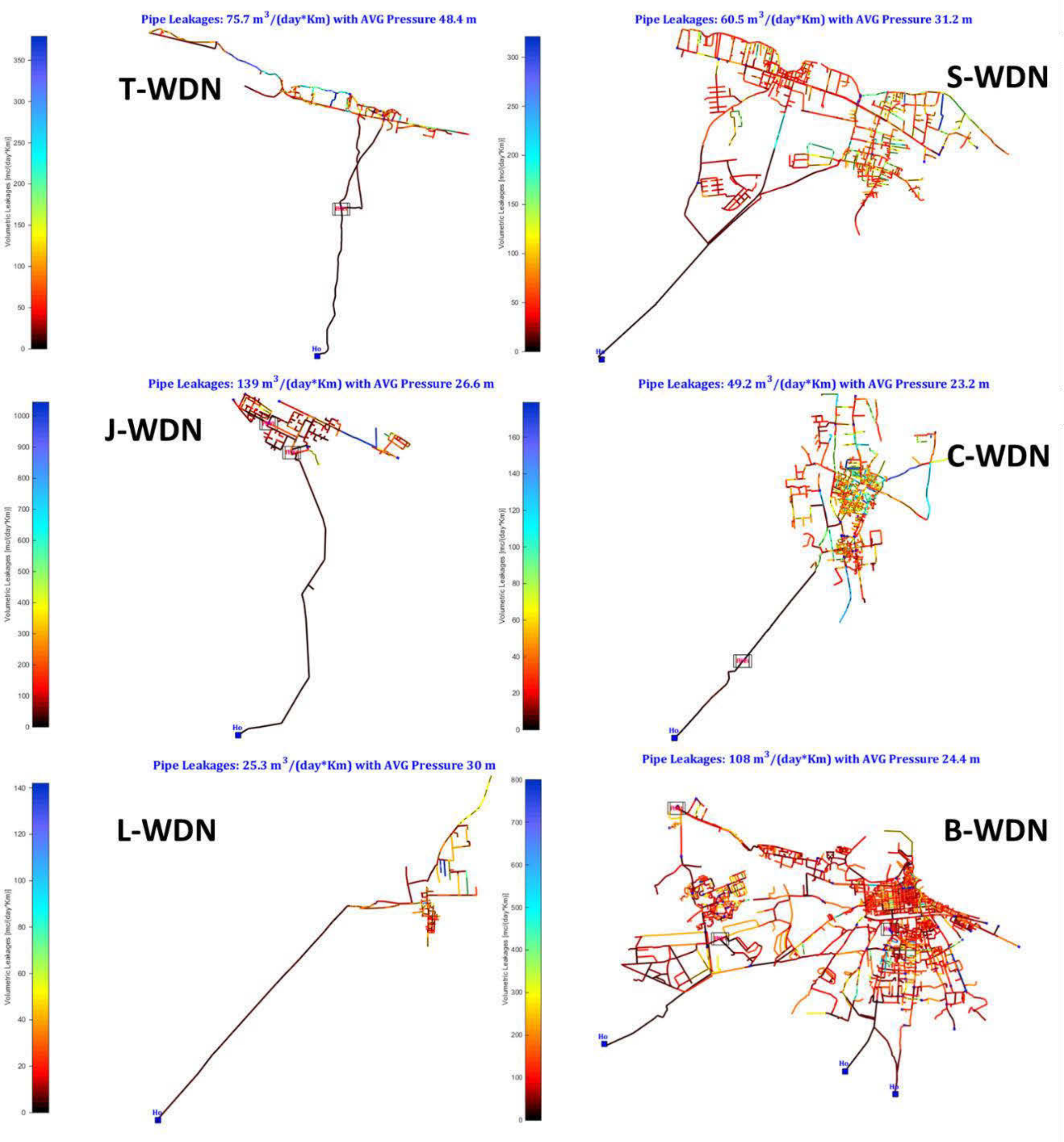

Figure 8. Calibration results: linear leakage indicator at single pipes for each WDN

5 CONCLUSIONS

This contribution presents the application of mass-balance approach for calibrating WDN hydraulic model in a real large WDN, which is composed of six sub-systems hydraulically disconnected form each other. The adopted approach allows getting consistent results with the expected hydraulic behaviour of the networks in terms of mass balance accounting for leakages and consumers' demand. This is of primary importance to get a phenomenological representation of the system to support next design of asset management actions.

The advanced WDN hydraulic model, based on pressure dependent representation of all outflow components, is the main driver to accomplish such an approach. The discussion about the calibration variables and the role of flow and pressure measurements, substantiated by results on the real WDN, demonstrates the following key points.

- The calibration of a WDN model to support asset management cannot represent leakages using fixed demand patterns. In fact, pressure regime changes day by day in consequence of the stochastic change of water requests.
- The robust estimates of parameters representing asset features (i.e., pipe hydraulic resistances and deterioration parameters in the leakage model), which can be assumed as invariant during the calibration reference period (e.g., one year), need to be performed across multiple operating cycles representing characteristic system functioning.
- Flow measurements play a crucial role in mass-balance calibration, while pressure data are useful to get consistent identification of leakage outflow component and, consequently, leakage model parameters.

The analysis of results on the real WDN demonstrate that the mass-balance approach for calibration helps the identification of unexpected results due to possible erroneous information or missing data. This represents a powerful tool to identify possible corrections on available information to be verified on the field, which can help the understating of actual WDN behaviour. Such a *reverse engineering* process was proved also in other real WDNs analysed during the same procedure by the authors.

ACKNOWLEDGMENTS

This paper was partly financed by European Union - PON Ricerca e Innovazione 2014-2020 E FSC, call D.D. 13 July 2017 n. 1735, Project "Energidrica - Efficienza energetica nella gestione delle reti idriche" (code ARS01_00625). Data for figures were provided by IDEA-RT (www.idea-rt.com).

6 REFERENCES

[1] Rossman, L. A., Epanet2 Users Manual. EPA, Cincinnati, USA, 2000.

[2] Todini, E., "A more realistic approach to the 'extended period simulation' of water distribution networks", In: Advances in Water Supply Management (C. Maksmovic, D. Butler & F. A. Memon, eds). A.A.Balkema Publishers, Lisse, The Netherlands, 2003, pp. 173–184.

[3] Giustolisi, O. and Walski, T., "Demand components in water distribution network analysis", J. Water Res. Plan. Manage, vol. 138, no. 4, 2012, pp. 356–367.

[4] Wagner, J. M., Shamir, U. and Marks, D. H., "Water distribution reliability: simulation methods", J. Water Res. Plan. Manage., vol. 114, no. 4, 1988, pp. 276–294.

[5] Germanopoulos, G., "A technical note on the inclusion of pressure-dependent demand and leakage terms in water supply network models", Civil Engineering Systems, vol. 2, 1985, pp. 171–179.

[6] Giustolisi, O., Savic, D. A. and Kapelan, Z., "Pressure-driven demand and leakage simulation for water distribution networks", J. Hydraulic Engineering, vol. 134, no. 5, 2008, pp. 626–635.

[7] Ulanicki, B., Bounds, P. L. M., Rance, J. P. and Reynolds, L., "Open and closed loop pressure control for leakage reduction", Urban Water Journal, vol. 2, no. 2, 2000, pp. 105–114.

[8] Giustolisi, O., Ugarelli, R., Berardi, L., Laucelli, D. and Simone, A., "Strategies for the electric regulation of pressure control valves", J. Hydroinformatics, vol. 19, no. 5, 2017, pp. 621–639.

[9] Ferrari, G., Savic, D. A., and Becciu, G. 2014, Graph-Theoretic Approach and Sound Engineering Principles for Design of District Metered Areas. J. Water Res. Plan. Manage. 140(12), 04014036.

[10] Laucelli, D., Simone, A., Berardi, L., and Giustolisi, O., "Optimal Design of District Metering Areas for the Reduction of Leakages", J. Water Res. Plan. Manage., vol. 143, no. 6, 2017, pp. 04017017-1-12

[11] Shamir, U. and Howard, C.D.D, "Water distribution systems analysis", J. Hydraul. Div., Am. Soc. Civ. Eng., vol. 94, no. 1, 1968, pp. 219–234.

[12] Walski, T. M., “Technique for calibrating network models”, J. Wat. Res. Planning and Management, vol. 109, no. 4, 1983, pp. 360–372.

[13] Kapelan, Z., Savic, D. A. and Walters, G. A., “Calibration of water distribution hydraulic models using a Bayesian-type procedure”, J. Hydraulic. Engineering, vol. 133, no. 8, 2007, pp. 927–936.

[14] Alvisi, S. and Franchini, M., “Pipe roughness calibration in water distribution systems using grey numbers”, J. Hydroinformatics, vol. 12, no. 4, 2010, pp. 424–445.

[15] Sanz G., and Pérez, R., “Demand pattern calibration in water distribution networks”, Procedia Engineering, vol. 70, 2014, pp. 1495-1504.

[16] Sanz, G., and Pérez, R., “Sensitivity Analysis for Sampling Design and Demand Calibration in Water Distribution Networks Using the Singular Value Decomposition”, J. Water Resour. Plan. Manage., vol. 141, no. 1, 2015, pp. 04015020.

[17] Cheng, W., and He, Z., “Calibration of Nodal Demand in Water Distribution Systems”, J. Water Res. Plann. Manage., vol. 137, no. 1, 2011, pp. 31-40.

[18] Rokstad, M.M. and Ugarelli, R.M., “Investigation of the Ability to Accurately Estimate Background Leakage Parameters in WDS Network Simulation Models”, J. Water Res. Plan. Manage., vol. 143, no. 4, 2017, pp. 04017002.

[19] Berardi L., Simone A., Laucelli D. and Giustolisi O., “Feasibility of mass balance approach to Water Distribution Network model calibration”, in XVIII International Conference on Water Distribution Systems, WDSA2016, Procedia Engineering, vol. 186, 2017, pp. 551–558.

[20] Berardi, L. and Giustolisi, O. “Calibration of Design Models for Leakage Management of Water Distribution Networks”, Water Resources Management, vol. 35, 2022, pp. 2537–2551.

[21] Girard, M. and Stewart, R. A. “Implementation of pressure and leakage management strategies on the Gold Coast, Australia: case study”, J. Water Res. Plan. Manage., vol. 133, no. 3, 2007, pp. 210–218.

[22] WDNetXL, http://www.idea-rt.com/digital-water-latest-innovation, May 2022.

[23] Berardi L., Simone A., Laucelli D. B., Ugarelli R. M., and Giustolisi O., “Relevance of hydraulic modelling in planning and operating real-time pressure control: case of Oppegård municipality”, J. Hydroinformatics, vol. 20, no. 3, 2018, pp. 535–550.

[24] Todini, E., “Extending the global gradient algorithm to unsteady flow extended period simulations of water distribution systems”, J. Hydroinformatics, vol. 13, no. 1, 2011, pp. 167–180.

[25] Giustolisi, O., “Water Distribution Network Reliability Assessment and Isolation Valve System”, J. Water Res. Plan. Manage., vol. 146, no. 1, 2020, pp. 04019064.

[26] Giustolisi, O., Berardi, L., and Laucelli, D., “Modeling local water storages delivering customer-demands in WDN models”, J. of Hydraulic Engineering, vol. 140, no. 1, 2014, pp. 89-104.

[27] Van Zyl, J.E., and Cassa, A.M., “Modeling elastically deforming leaks in water distribution pipes”, Journal of Hydraulic Engineering, vol. 140, no. 2, 2014, pp. 182-189.

[28] Todini, E., “Using a Kalman Filter Approach for Looped Water Distribution Network Calibration”, in Proceeding of Water Industry Systems: Modelling and Optimisation Applications, Exeter, UK, D. A. Savic and G. A. Walters, eds., vol.1, 1999, pp.327-336.

[29] Autorità di Regolazione per Energia Reti e Ambiente (ARERA), Delibera 917/2017/R/IDR - Regolazione della qualità tecnica del servizio idrico integrato ovvero di ciascuno dei singoli servizi che lo compongono (in Italian), 2017.