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-CCWI2022.2022.14776

DOMAIN ANALYSIS OF WATER DISTRIBUTION NETWORKS

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Abstract

Water Distribution Networks (WDNs) represent spatially organized infrastructures, whose main function is to deliver water from hydraulic sources to meet the customers' demands and pressure requirements of the system through interconnected pipes. The time-varying water demands and the asset deterioration greatly contribute to the complex functioning of WDNs. Nonetheless, the hydraulics of these system in strongly determined by the topology of pipelines, as represented by the connectivity among pipes and nodes.

The Complex Network Theory (CNT) has been recognized to provide a wide range of metrics for studying WDNs , only based on the analysis of the topological domain. In addition, some latest advancements on tailoring CNT metrics for WDNs have been introduced to understand hydraulic behaviour of such systems, even before performing classical hydraulic modelling.

This contribution deals with the application of some tailored centrality metrics, such as betweenness and edge betweenness for capturing the topological domain of WDNs. The analysis has been extended to each subnetwork of a large real WDN, to provide helpful elements for various tasks including the validation of available hydraulic models, and the identification of main water paths to support model calibration and planning of maintenance/retrain works.

Keywords
Water Distribution Networks, Complex Network Theory, Centrality Metrics.

1 INTRODUCTION

Water Distribution Networks (WDNs) in urban areas stands as the main fundamental infrastructures for different activities of life. In the last years, water utilities are facing several technical issues, particularly related to the increase of water demand, asset degradation and water leakages. All such issues concur to downgrade the performance of the whole system in terms of the reliability of the water supply service.

In order to ensure an adequate level of service, water companies are interested in procedures and products to improve the understanding of such systems and hence make the WDN management more effective and efficient.

The complexity of WDNs is related to many aspects, including their topological configuration and the hydraulic behaviour, which follows water requests from consumers and leakages due to asset deterioration and pressure. Indeed, the hydraulic phenomena that determine the level of water supply service in WDNs take place in networked pipelines. Therefore, WDNs topological domain strongly affects the hydraulic status throughout the system in terms of flows along pipes and pressure regime.

Assessing WDNs topology is known to provide effective understanding of WDNs hydraulic behavior [1][2][3], besides classical hydraulic modelling approach. This means that information on WDNs topology can provide useful insights from various planning and management tasks, ranging from WDNs model calibration up to possible improvements of service conditions.

In recent years, Complex Network Theory (CNT) has been introduced in WDNs analysis for an in-depth understanding of the network from a topological point of view. CNT has been previously developed and applied in various technical and research areas, even far from water systems; they include social networks [4], biological networks [5], informative networks [6], and spatial networks [7]. In the case of WDNs, it has been reported that CNT is suitable for detecting the emergent hydraulic behavior [8] and it has been applied for a wide range of operational tasks, including WDNs vulnerability and structure assessment [9] [10], WDNs solutions optimization [11], optimal district design [12] and water quality analysis assessment [13].

The basic idea of CNT leads to the conceptualization of the network as a graph, an ordered set of vertices interconnected by a set of edges, and the evaluation of some peculiar properties of the network topology through metrics, that were introduces to quantify the properties of network structure [14].

Among such metrics, the centrality metrics, firstly introduced by [15], represent the candidate measures for better understanding the features of the network by ranking the importance of the nodes [14]. The most adopted are: degree [15, 14], eigenvector [16], closeness [17], Katz centrality [18], and PageRank [19].

WDNs are spatial networks whose topology is bounded by the constraints of urban layout, which influence the nodal degree distribution [20].

As pointed out by [7], in case of spatial networks, like WDNs, the centrality metrics are more relevant to capture the flux of information. This happens because centrality metrics are built upon the concept of shortest path, representing the optimal path between two nodes using the minimum number of links. In the case of WDNs, the flux is represented by water flows along pipes, reaching nodes of the graph (where consumers demand is allocated in classical WDNs representation) from water sources (reservoirs, tanks, pumps).

In addition, differently from other networked systems, nodes and pipes in WDNs have different relevance in terms of hydraulic status. This fact, motivated to define some tailored metrics, such as [21], to take into account that those pipes/edges are physical components of the WDNs; some nodes (reservoirs and tanks) play a completely different hydraulic role from the majority of nodes (demand and connection nodes); and pipes have different characteristics (length, diameter, hydraulic resistance, etc.) that can be included in CNT metrics tailored for WDNs. Later on [22] provided a first application of the edge betweenness centrality metrics developer in [22] for analysing the spatial domain of the networks.

Recently, [23] pointed out that classical centrality metrics cannot exhibit the information associated to vertices and edges, because the relevance of the network elements, identified as the role among the community, is not considered. Therefore, [23] relaxed the assumption of identical relevance of edges and vertices and proposed a weighted version of these metrics for understanding the networks' behavior. This way, a relevance function has been introduced, which takes different formulations according to the type of the network, for capturing the interplay between the network topological structure and the intrinsic relevance of the elements of the network.

In this paper, two metrics tailored by [23] have been applied for the first time to analyse the topological domain of a large real WDN, composed by few subnetworks. The topological analysis has been compared to the hydraulic simulation results, proving the consistency of the proposed approach. Thus, the preliminary understanding of the WDN behavior based on topological domain analysis is demonstrated to provide a useful support for several tasks of WDN design, including asset management and planning, to be used in conjunction with classical hydraulic modelling.

2 METHODOLOGY

[23] draws the attention about the importance of considering the information about the intrinsic relevance of each node, as exogeneous data independent from the network topology layout, into the CNT metrics. The intrinsic relevance for each node, defined as R_n (*n=1, …, V*), is so assigned in different ways to nodes having different roles in WDN functioning. It is equal to the water demand supplied to each "demand node" and to the sum of supplied water demands for each "source node". In this way, all nodes assume a different relevance during the analysis, and the intrinsic-relevance metrics can be introduced using various formulations of the function $f(R_s,R_t)$ [23], where R_s and R_t represents the relevance of vertices *s* and *t*, respectively.

Some most adopted centrality metrics in WDNs analysis [24] have been applied in the relevance-embedded versions [23], however nodal and betweenness centrality metrics have demonstrated to detect well the WDN topological behavior [22].

The standard version of the betweenness centrality [15] assigns the number of shortest paths traversing a vertex *v* for all couples of vertices *s* and *t* of the network. Similarly, the edge betweenness, *EB(e)*, is the sum of the fractions for all the couples of vertices *s* and *t* of the network traversing an edge e. The classic formulations of these metrics, for a vertex *v* and edge *e* respectively, are reported below:

$$B(v) = \sum_{s \neq v \neq t \in N} \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{1}$$

$$EB(e) = \sum_{s \neq t \in N} \frac{\sigma_{st}(e)}{\sigma_{st}} \tag{2}$$

The relevance-embedded versions of such metrics are carried out by weighting them with the relevance function $f(R_s, R_t)$, which formulations are reported in [23], calculated as follows:

$$B(v) = \sum_{s \neq v \neq t \in N} f(R_s, R_t) \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{3}$$

$$EB(e) = \sum_{s \neq t \in N} f(R_s, R_t) \frac{\sigma_{st}(e)}{\sigma_{st}} \tag{4}$$

where the intrinsic relevance terms of $f(R_s, R_t)$ function are assigned as in [23], i.e. equal to the customer water demand for each "demand node" of the network and the sum of supplied water demands for the "source node". Among the formulations of the relevance function, the $f(R_s, R_t)= R_s \cdot R_t$ one fits well the relevance domain of the network [23], and it is herein applied for the analysis of the domain characteristics of the network.

3 CASE STUDIES

The domain analysis reported above has been applied to a real-life WDN of a large city in Southern Italy. It was part of a workflow for asset management activities aiming at DMA design and pressure control for leakage reduction, with possible improvements of system hydraulic functioning.

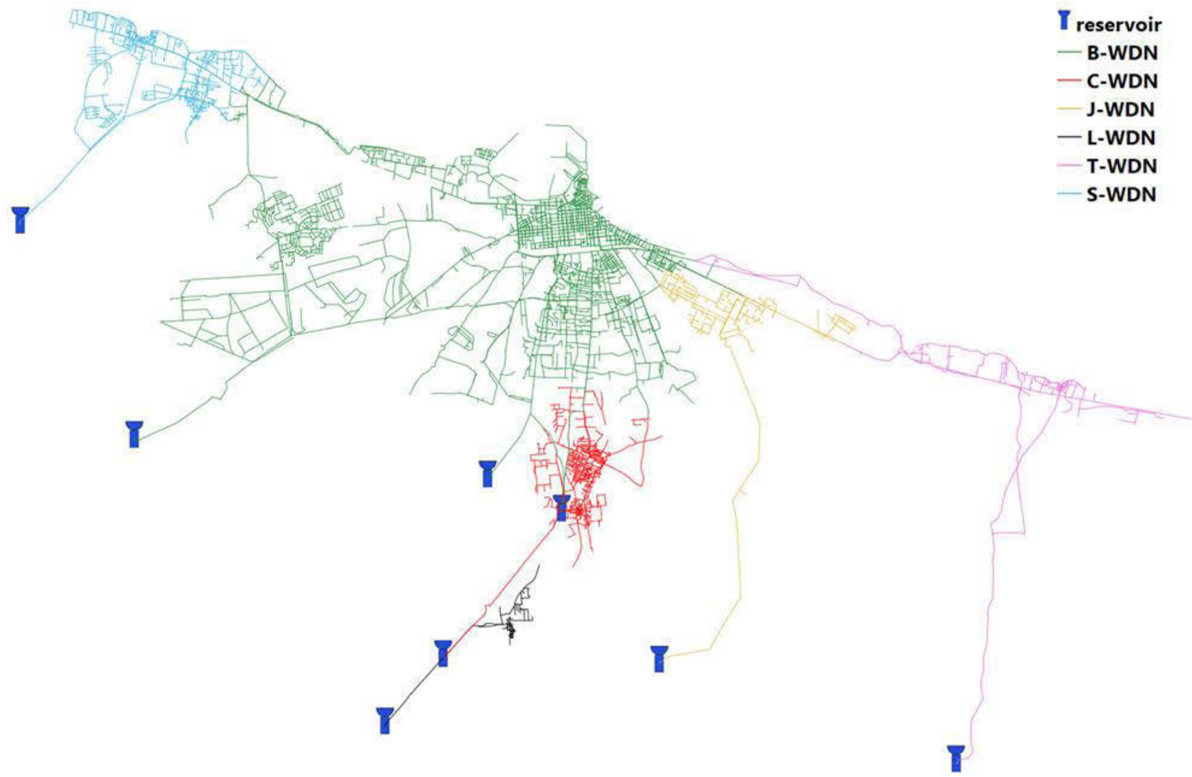

Figure 1. Visualization of the real WDN layout and its sub-networks.

The WDN is composed of six subnetworks fed by eight reservoirs; the total length of the whole network is about 700km, with 7 pressure reduction valves. The system also includes about 80 partially closed valves and 150 closed gates. Figure 1 shows the six subnetworks and Table 1 summarizes key data for each corresponding WDN hydraulic model.

Previous metrics has been applied to the whole set of subnetworks singularly, with respect to each one hydraulic layout, which comprises its own sources and pipelines. Indeed, relevance-embedded centrality metrics are weighted with the relevance terms R_n of nodes. The results of the domain analysis have been compared with the hydraulic simulation of each network.

The hydraulic analysis has been performed using the WDNetXL platform [25][26], which allows a phenomenological representation of the hydraulic behavior of the network by representing the volumetric leakages as a function of the average pressure and pipe deterioration, at single pipe level, and including different types of users' connection (i.e. direct connection to WDN, free orifices, private tanks) or insufficient pressure conditions for correct service.

Table 1. Data of WD hydraulic model of each subnetworks

Subnetwork	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

Figures 2 and 3 show the comparison between the representations of the relevance-embedded edge betweenness (3) and the hydraulic simulation outputs of the main pipe flows for each subnetwork. It is worth noting that higher values of edge betweenness, ranging from 65-100%, are related to the higher supplying paths. This is emphasized in the smaller WDNs cases, J-WDN, L-WDN, C-WDN and T-WDN, where the paths with edge betweenness values, about 75-100%, fits with pipes supplying the main amount of demand of each network.

In case of the B-WDN, which is the biggest one fed by three source nodes, the main feeding lines show different relevance values, which are consistent with the lines traversed by the highest average flow rates. This, in turn, confirm the main structure of the system behaviour as built, consistently with the information reported by the personnel of the water utility.

In the case of J-WDN, it has to remark that the main feeding line from the reservoir shows two different values of the relevance (i.e. tailored edge betweenness) for the upstream and the downstream half of that line. In more details, the upstream half shows a lower relevance than the downstream half. This happens because at about half of that pipeline there is a big demand node representing the feeding of another small city. Therefore, such node has high nodal relevance which affects all the shortest paths traversing the downstream half of the feeding pipeline only, according to formulation (4).

This circumstance confirms that the domain analysis, although largely consistent with the hydraulic behaviour of the system, cannot replace the physically-based modelling of WDN functioning, which unveils also flow directions.

Figures 4 and 5 show the comparison between the representations of the relevance-embedded nodal betweenness (4) and the hydraulic simulation outputs of the main pipe flows for each subnetwork, which confirms the observations, mentioned above in the case of the edge betweenness, where main flow paths of each network pass through the nodes with higher betweenness values.

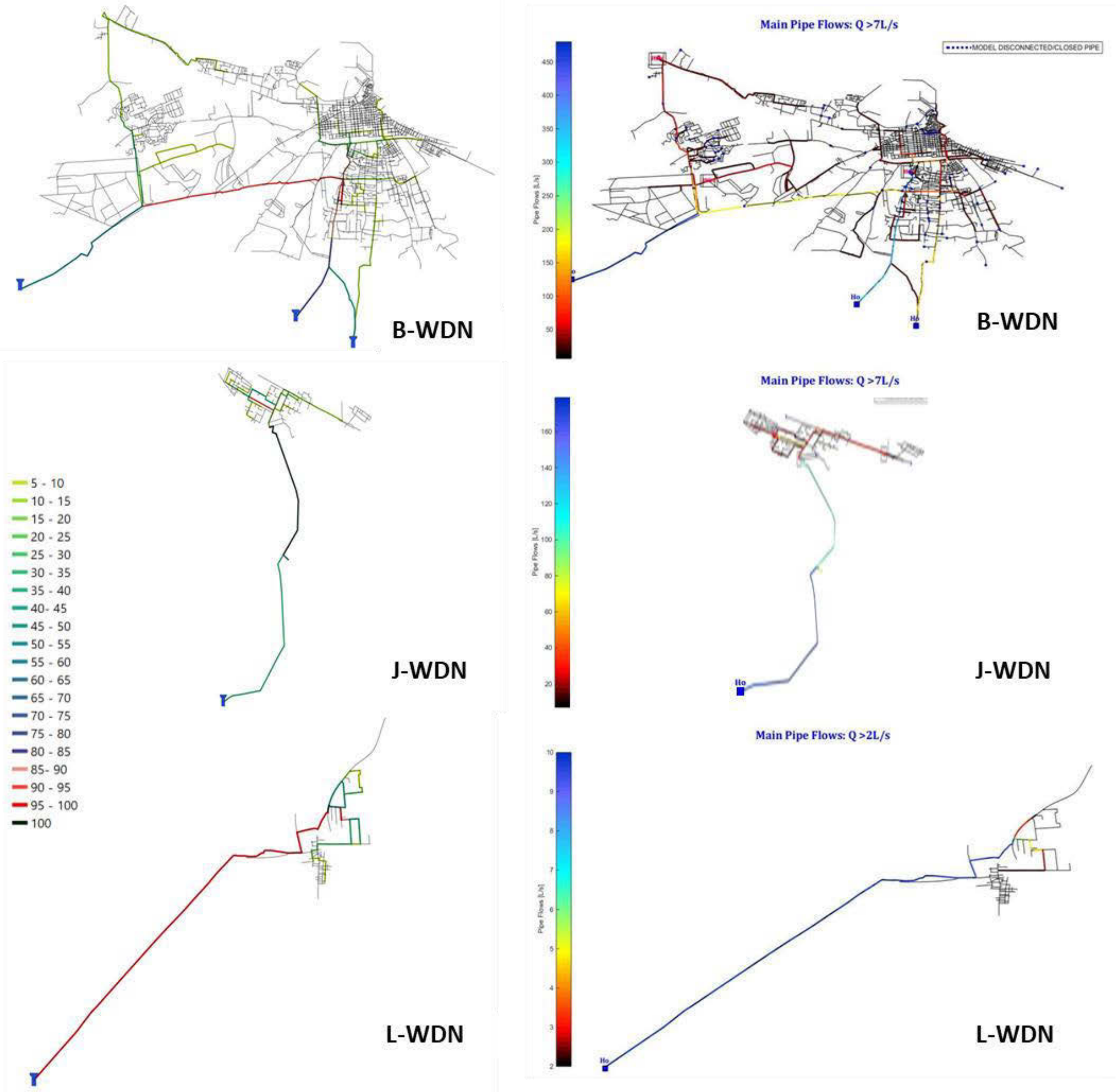

Figure 2. Comparisons between the relevance-embedded edge betweenness and main pipe flows simulation for B-WDN, J-WDN and L-WDN.

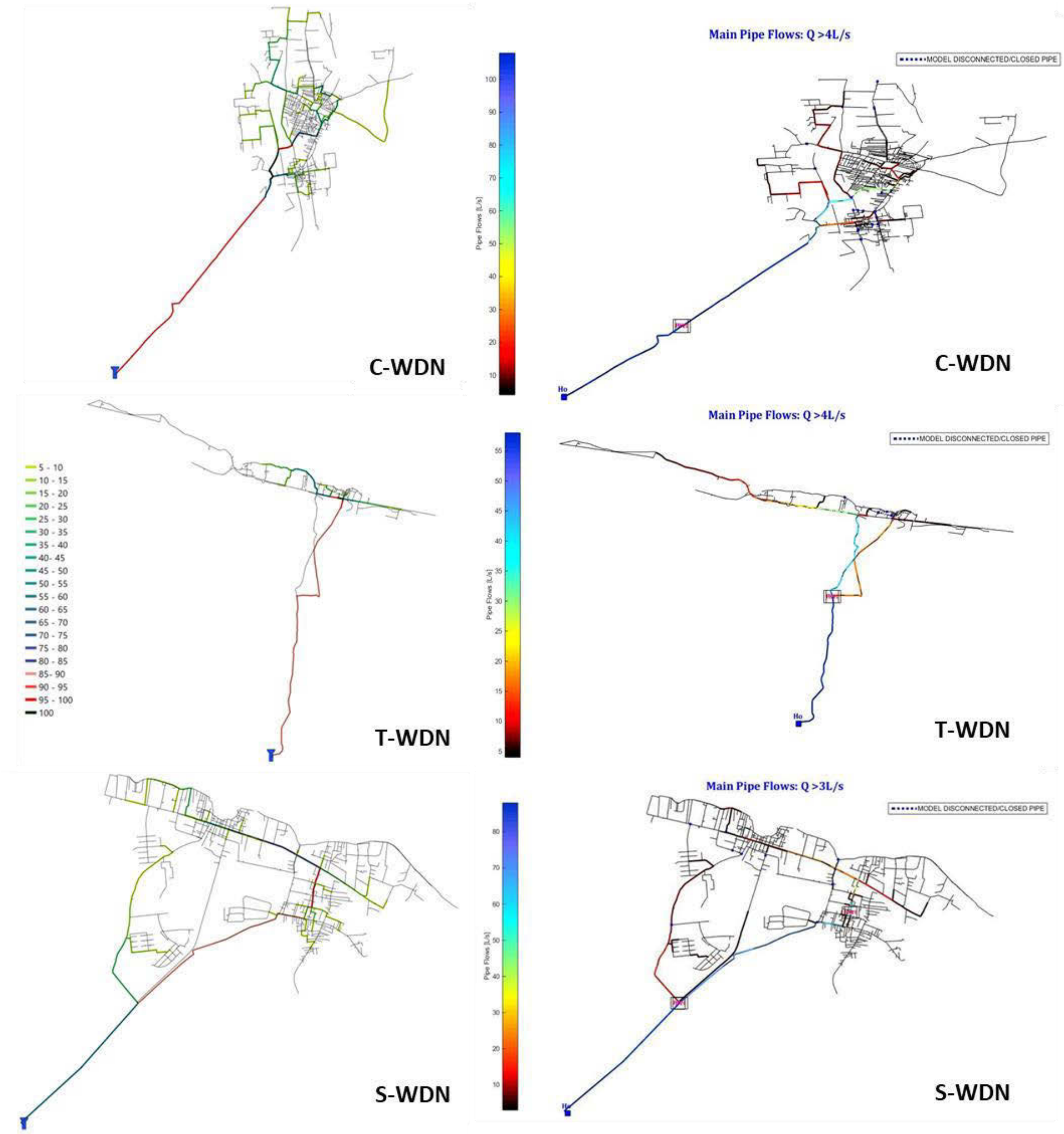

Figure 3. Comparisons between the relevance-embedded edge betweenness and main pipe flows simulation for C-WDN, T-WDN and S-WDN.

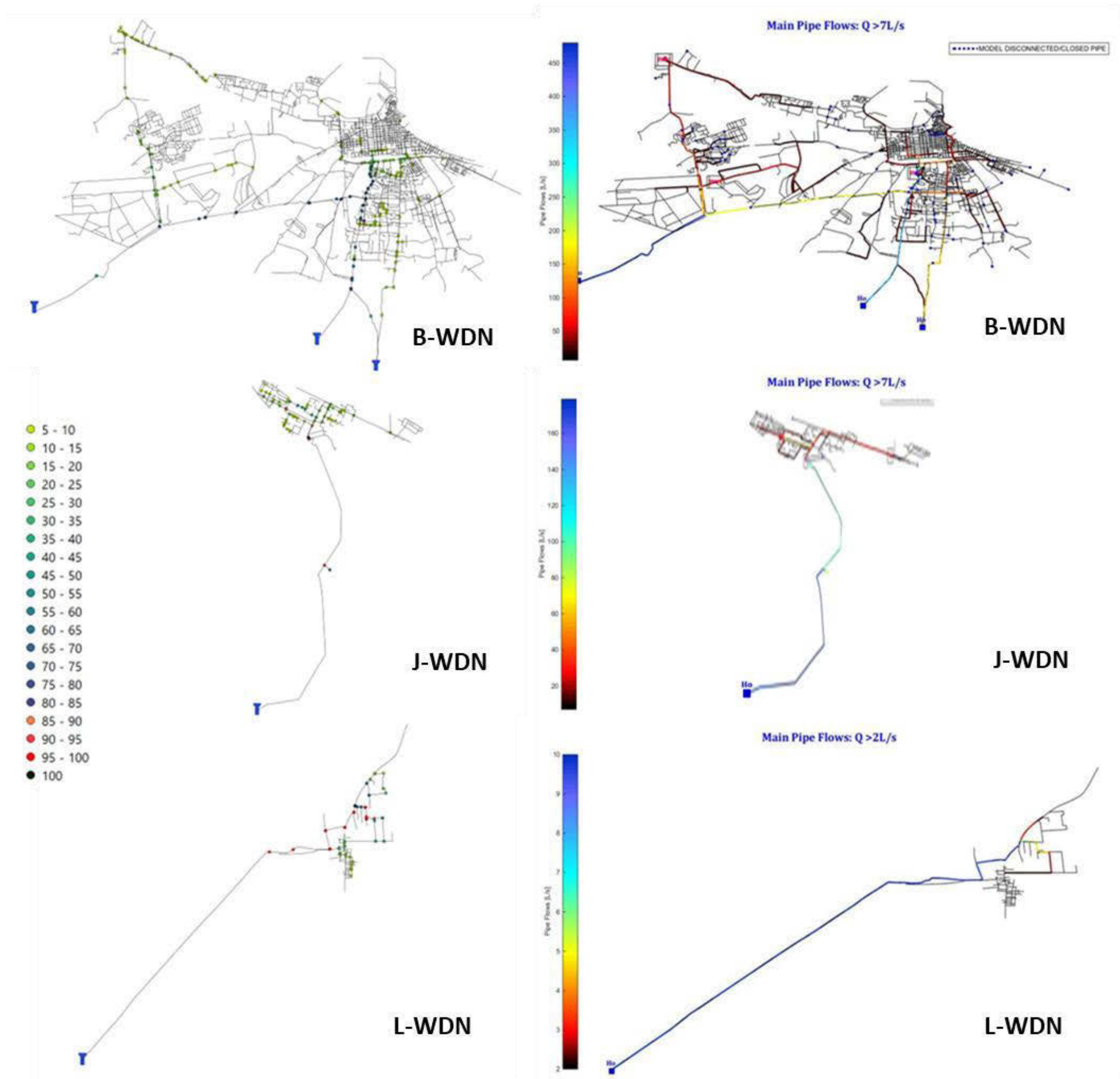

Figure 4. Comparisons between the relevance-embedded betweenness and main pipe flows simulation for B-WDN, J-WDN and L-WDN.

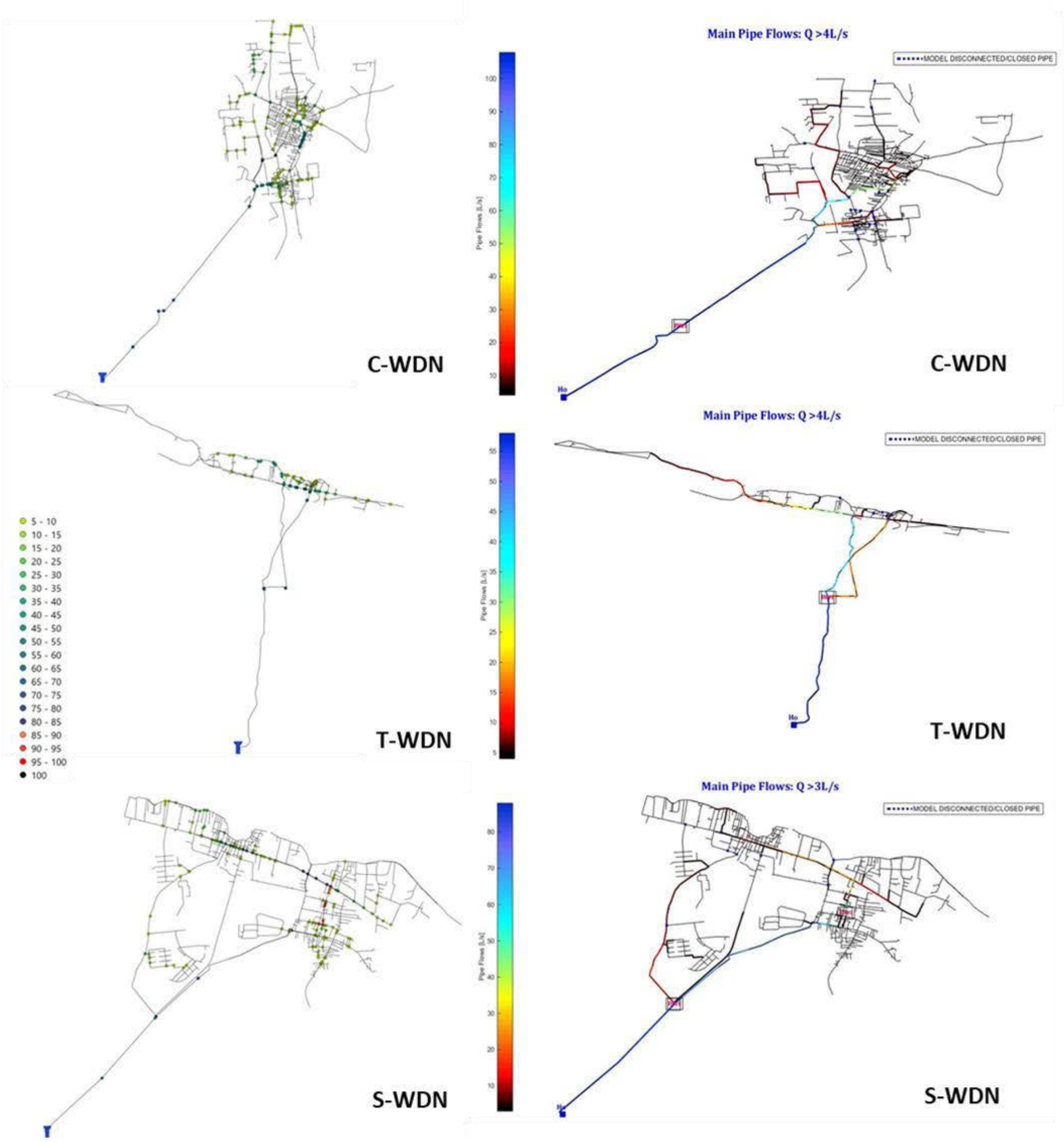

Figure 5. Comparisons between the relevance-embedded edge betweenness and main pipe flows simulation for C-WDN, T-WDN and S-WDN.

Finally, Figures 6 and 7, provides a comprehensive view of the original large WDN, showing the results discussed above. Such analyses, provided some preliminary information to drive for several operational and design tasks in each sub-system.

In case of model calibration, the most relevant pipes unveiled by domain analysis are those deserving accurate assessment of hydraulic resistance. In fact, they are traversed by highest flows and usually are quite long pipelines. Therefore, the head-losses along such lines strongly affect pressure regime in the main distribution part of the system and, consequently, the calibration of leakage model parameters [25]. *Viceversa*, pipes into the main looped distribution part of the WDN are assigned with lower relevance because there are many alternative paths connecting nodes with similar low relevance. For these reasons, from calibration perspective, the accurate assessment of their hydraulic resistance values has not a relevant impact on WDN hydraulic behaviour.

The visual identification of the main flow paths circulation provides also useful information about possible improvements in WDN supply service performances. For instance, in case of T-WDN, the rightmost part of the distribution network, which was reported to suffer from pressure deficit conditions, has a low relevance from domain analysis. This allowed to explore a possible change in global WDN configuration, where that part of the T-WDN is fed by the J-WDN. In fact, from domain analysis perspective, this change is going to not affect the main flow paths in T-WDN, while generating increase in pressure at demand nodes because of higher pressure in J-WDN.

In the case of DMA design, pipes with higher relevance represents pipes where closed sectioning valves should be avoided in order to not modify abruptly the existing hydraulic scheme. For the same reason, i.e. highest flows circulating along the most relevant pipes, they can be candidate for installing affective flow meters at DMA boundaries, since they are not affected by flow inversion thus minimizing uncertainties in DMA bass balance evaluation.

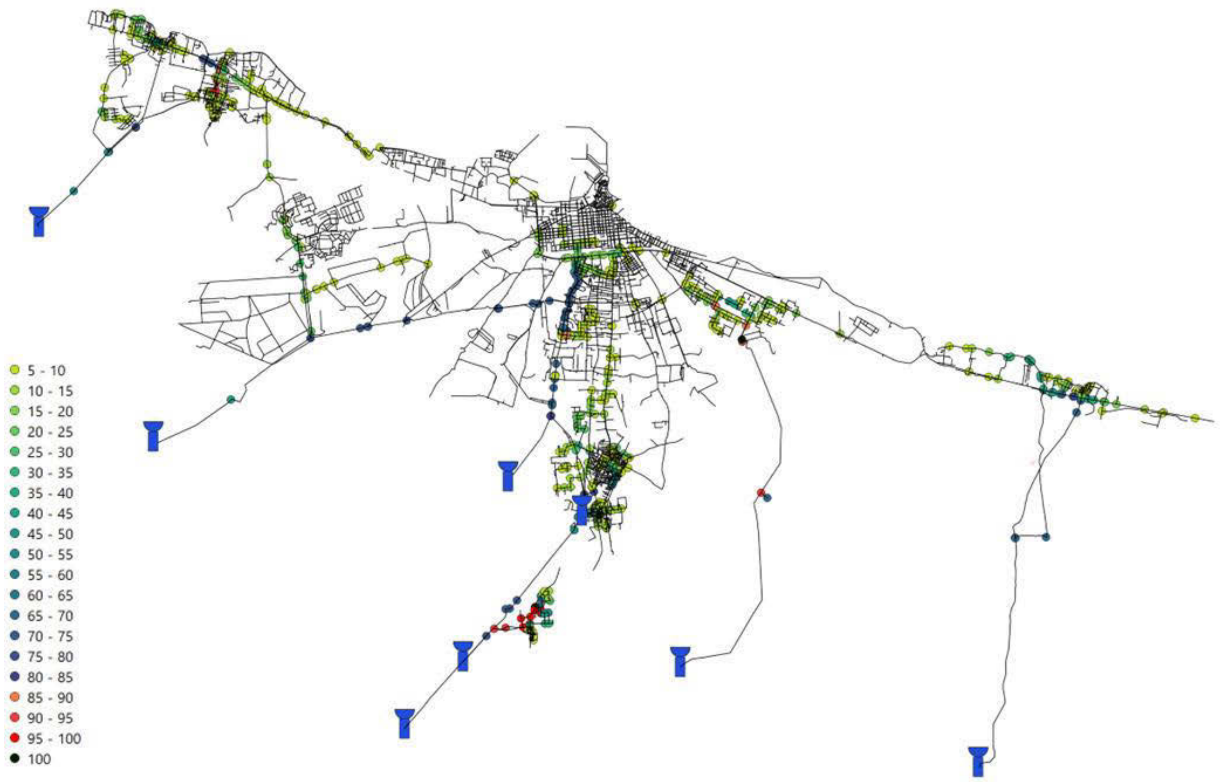

Figure 6. Visualization of the relevance-embedded betweenness centrality for the WDN case study.

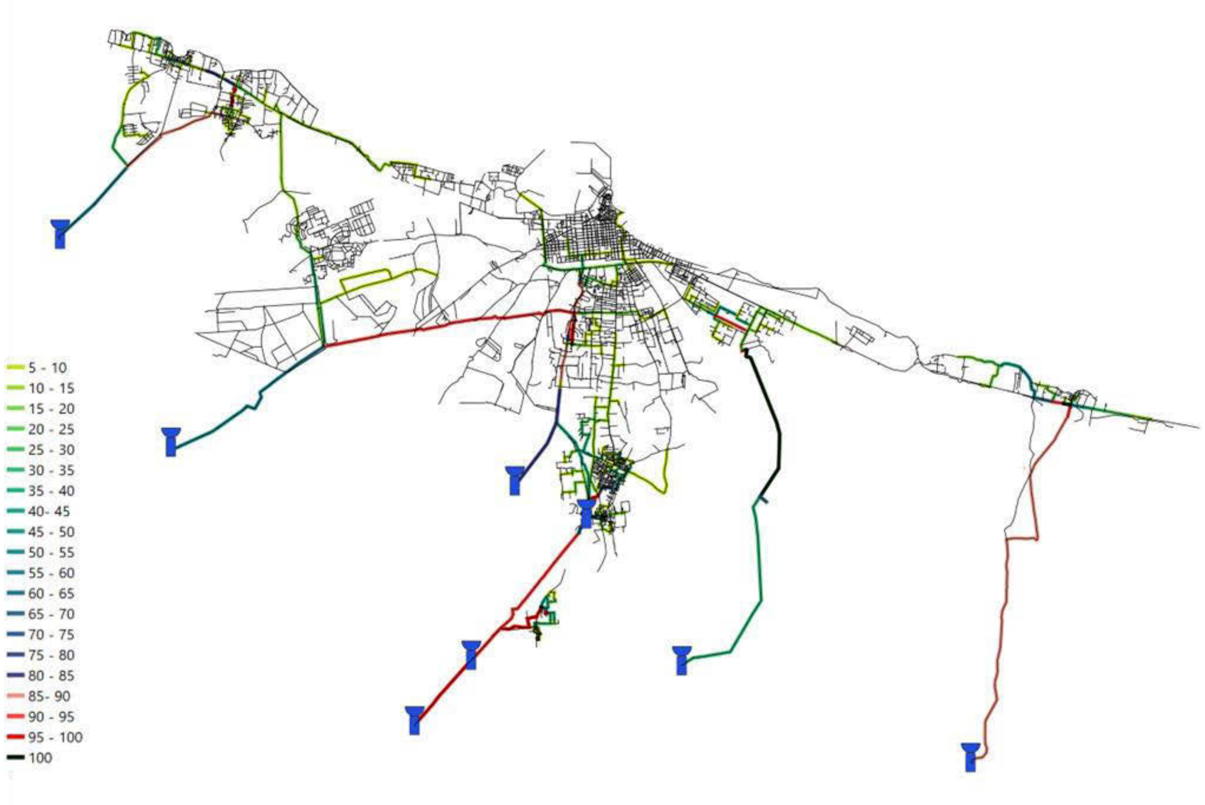

Figure 7. Visualization of the relevance-embedded edge betweenness centrality for the WDN case study.

4 CONCLUSIONS

In this work is presented the application of the domain analysis in a real large WDN, which is composed of six sub-systems hydraulically disconnected from each other. That analysis encompasses the evaluation of two relevance-embedded centrality metrics, weighted according to the formulation proposed by [23], for analysing the emergent hydraulic behavior of WDNs without performing any hydraulic simulation. Results show that it allows getting consistent outcomes through the comparison with the expected hydraulic behaviour, accounting for the simulated pipe flows along the networks. In particular, it has been reported that higher values of centrality metrics for pipes and nodes fit with the main simulated flow paths and demand nodes. The ability to capture the hydraulic behavior, only using the topological analysis, can be useful as a preliminary step for supporting WDNs operational and planning tasks.

Using a large real-life system, also revealed that such analysis can support various planning and management tasks, while it cannot replace the phenomenological representation provided by the hydraulic modelling, which is mandatory to validate each phase of the design workflow.

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).

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