EPiC Series in Engineering
Volume 3, 2018, Pages 582–592
HIC 2018. 13th International Conference on Hydroinformatics

An advanced software to manage a smart water network with innovative metrics and tools based on social network theory

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Abstract. The recent development and applications of social network theory in many fields of engineering (electricity, gas, transport, water, etc.) allows both the understanding of networks and to improve their management. Social network theory coupled to the availability of real time data and big data analysis techniques can change drastically the traditional approaches to manage civil networks. Recently, some authors are working to apply this novel approach, based on social network theory, on the water distribution networks using: a) graph partitioning algorithms to define optimal district meter areas both for water losses identification and for water network protection, b) innovative topological, energy and hydraulic indices to analyze performance; and c) GIS (Geographical Information System) to provide a more effective display of results and to improve network behavior in specific operational conditions. In this paper, a novel release 3.5 of SWANP software, that implements all these features, was tested on a real large water network in Alcalá de Henares, Spain.

Keywords: smart water network, social network theory, water partitioning, water protection, performance indices

1 Introduction

In the last years, three lines of research and development (real time data acquisition; big data analysis and social network theory) are changing significantly the understanding and management of social and civil networks. The paradigm of Smart City [1] seems now possible due to low cost smart sensors [2] able to measure in real time, and the growth of computational power able to analyse big data and to apply complex network theory, allowing to understand some crucial aspects of very large networks in terms of reliability and robustness [3].

These innovative technological aspects have recently allowed defining the novel paradigm of Smart WAter Network (SWAN) [3] referring to all water networks that implement on-line smart sensors and decision support systems. The novel paradigm of SWAN is especially effective in Water Distribution Networks (WDN) that show very high extension and level of connections (loops).

The novel Information and Communication Technologies (ICT) simplify the implementation of the "divide and conquer" technique [3] – consisting of dividing a water network into *k* smaller subsystems or District Meter Area (DMA) by gate valves and flow meters – that allows improving significantly the WDN management making real the paradigm of SWAN. Indeed, as known, the definition of DMA represents one of the most effective strategy [4,5] to simplify the control of real (physical) water losses obtained essentially with four actions: a) conducting pressure management, b) achieving active leakage control, c) improving the speed and quality of leak repairs, and d) increasing main replacement and rehabilitation. Furthermore, the definition of DMA also allows to reduce the risk of malicious or accidental contamination of a water supply network [2]. The network partitioning allows the activation of protection measures since it is possible to disconnect only some part of the network [2]. Finally, the definition of DMA allows monitoring the water demand and hydraulic performance for each district separately improving the system knowledge and, consequently, planning the ordinary and extraordinary maintenance.

The design of DMA is traditionally based on empirical suggestions (such as the maximum number of properties or total length of pipes in a DMA) combined with trial-and-error procedures, where the pipes to be closed are preventively chosen and a simulation model of the distribution network is run repeatedly until a feasible solution in terms of pressure and flow is developed. This approach is very difficult to apply to large water supply networks [3] without a significant alteration of hydraulic performance of the system due to the reduction of topological (network loops) and energy (diameter sections) redundancy [3, 6]. Traditional software, available on the market, provide no tools to define optimal partitioning or sectorization, no information about topological or energy characteristics of the network, and, finally, no functionality to analyse actions for water protection from accidental or intentional contaminations.

Additionally, novel approaches and methodologies borrowed from social network theory [7] can provide useful metrics, properly weighting the links and nodes of the network, the local and global system behaviour. In recent years, some applications in water distribution network partitioning have been applied successfully to optimal design of DMAs [8, 9, 10 ,11].

In this paper, social network theory was used to analyse and automatically define the optimal layout of network DMA improving the release 3.5 of SWANP (Smart WAter Network Partitioning and Protection) software.

In particular, in collaboration with AQUALIA company, SWANP 3.5 was tested on large water network of Alcalá de Henares in Spain, showing some advantages in the analysis, partitioning and visual displaying of the case study.

2 Methods

The first and third release of SWANP software [12], developed in Python v2.7 language, provided the decision-maker different solutions to define automatically the optimal layout of DMA both for water losses and water protection, using some partitioning algorithms and several hydraulic and energy indices. The last release 3.5 of SWANP software implements novel algorithms, to define optimal water partitioning, and a number of novel topological indices, to compare the original and partitioned network and better analyse the network behaviour with reference to robustness issues. A full integration in a QGIS framework was implemented, that improves significantly the results display.

SWANP 3.5 software provides an easy tool to compute the optimal water network partitioning based on two different phases [13]: a) the clustering, aimed at defining the shape and the dimensions of each DMA; b) the dividing, aimed at physically partitioning the network, by selecting pipes for the insertion of flow meters or gate valves.

In SWANP 3.5 a new algorithm for the clustering phase was implemented based on community detection. Sociologists apply these algorithms to uncover community structure in social network (SN) [7]. Community or module, C, can be described as a group of nodes with high density of links between them and low density of link between different groups (or communities).

As a social network, also a water supply network can be represented as a simple graph $G=(V,E)$, where V is the set of n vertices (or nodes) and E is the set of m edges (or links), or as a weighted graph, if some vertices or edges have associated weights. The problem of uncover k communities in a social network, can be related to the problem of dividing a water distribution network into DMAs, but while in a SN the number k is previously unknown, for a WDN the number k can depend on economic and management considerations [14] and it can previously assigned.

In the last years, many authors have proposed different methodology to identify the community structure of a network; an extensive comparative analysis is provided by

Yang et al. [15]. In SWANP 3.5, *fast greedy* (FG) algorithm [16], available in igraph package (a network analysis tool in Python) [17], was implemented for the clustering phase.
Specifically, to discover communities in the network, FG algorithm maximizes the modularity metric Q [16], defined as:

$$Q = \frac{1}{2m}\sum_{ij}\left(A_{ij} - \frac{K_i K_j}{2m}\right)\cdot\delta_{ij} \tag{1}$$

where δ_{ij} is 1 if $i=j$ and 0 otherwise, A_{ij} is an element of the adjacency matrix of network (A_{ij}=1 if i and j are linked, A_{ij}=0 otherwise), K_i is the degree of vertex i, defined as the number of links connected to node i and K_j is the degree of node j. As known, values of modularity higher than 0.3 indicate a good community structure in the network [18]. A most common formulation of modularity metric, derived from Eq. (1), is the following:

$$Q = \sum_{i}\left(e_{ii} - a_i^2\right) \tag{2}$$

where e_{ij} is the fraction of edges in the network that connect vertices in the same community i and a_i is the fraction of edges with at least a vertex belonging to community i [16].
The FG algorithm uses a greedy optimization to maximize the modularity: starting with a number of communities equal to the number of vertices in the network, two communities are merged if their amalgamation increases the modularity. The algorithm stops after $n-1$ merger and only a single community is left.
In collaboration with AQUALIA, the following weights were previously assigned to each pipe, during the clustering phase:

- no-weight, W_1;
- pipe diameter D_{ij}, W_2;
- number of users supplied by each pipe ij, W_3, computed as follows:

$$w_{ij} = \frac{s_i}{k_i} + \frac{s_j}{k_j} \tag{3}$$

in Eq. (3), s_i and s_j are the number of customers supplied by node i and j, k_i and k_j are the degree of the nodes linked by pipe ij.
The second phase, the dividing, consists in to define the best position of the flow meters and gate valve to insert in the boundary pipes (or edge-cuts) between districts previously obtained by clustering algorithms. In this way, a physical partitioning of

water network is carried out. This goal is achieved by means a Genetic Algorithm (GA) [19] in order to maximize the total node power of the network:

$$FO = \gamma \sum_{i=1}^{n} Q_i H_i \tag{4}$$

where γ is the specific weight of water, Q_i and H_i are the water demand and head at each network node. SWANP 3.5 allows to compute some traditional and innovative Performance Indices (PI) that provide information both on the whole network and on a sub-system or DMA: Topological, Energy, Hydraulic and Protection Performance indices. Figure 1 shows the GUI of SWANP 3.5 concerning the calculation of PIs.

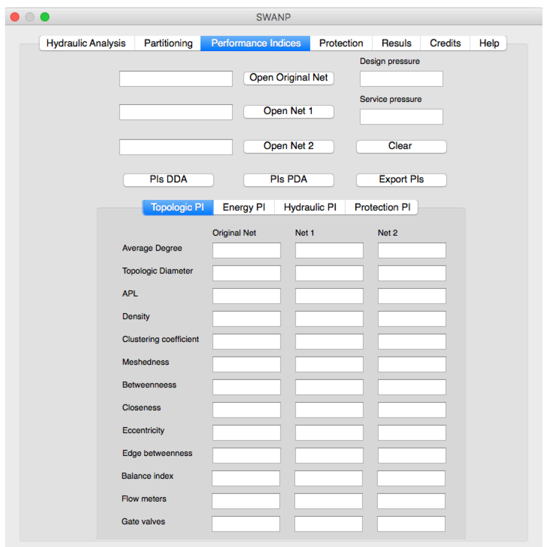


Figure 1 Water network layout modelled in SWANP 3.5

In this study, some of these metrics were computed to analyse the water network performance in terms of local and global performance. Topological performance indices, measured by the number of nodes belong to each cluster C, n_i; balance index, I_b defined as follows:

$$I_B = \frac{k \cdot \max\left(d_p\right)}{n} \tag{5}$$

where $max(d_p)$ is the size of largest cluster; demand balance index I_d computed by means Eq. (5) replacing $max(d_p)$ with the maximum supplied demand among clusters and n with the total supplied demand in the network; total number of boundary pipes (edge-cut set), N_{ec}, modularity index Q, computed by relation (2), Average Path

Length (*APL*) which represents the average number of steps along the shortest paths for all possible pairs of nodes and provide information about how much a network is fragmented [20]; *APL* deviation, Δ_{APL}, that quantifies the *APL* deviation of partitioned network layout from original network [11].

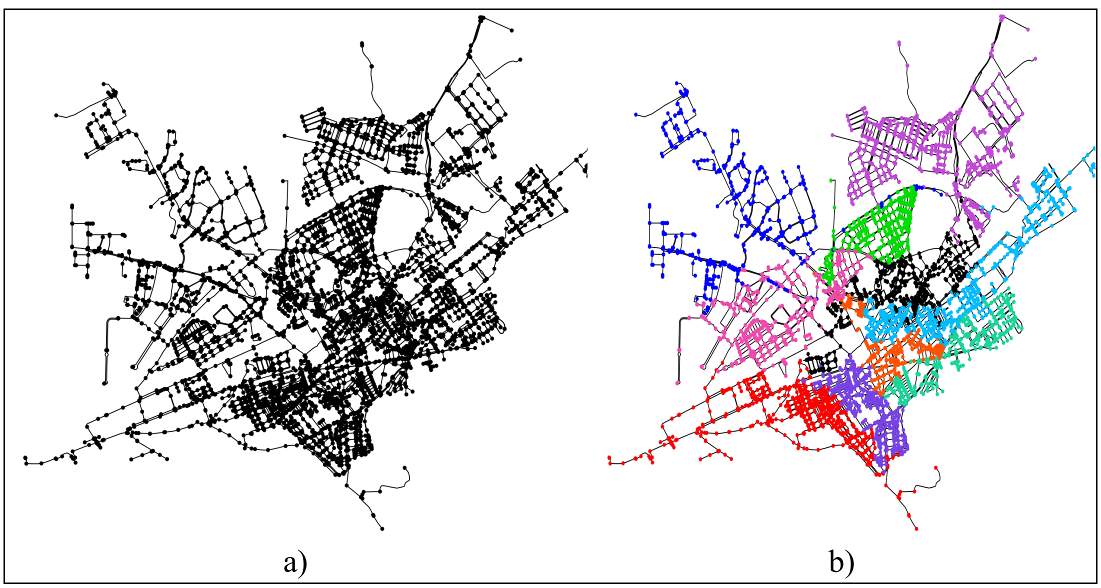
Energy performance indices measured by: resilience index I_r [21], based on the comparison between the surplus of hydraulic power available at nodes and the maximum hydraulic power available in the to satisfy the total users demand; the resilience deviation index I_{rd} [22] – based on the comparison among the resilience indices of the original and partitioned network.

Hydraulic performance indices measured traditionally by mean node pressure, h_{mean}, maximum node pressure, h_{max}, minimum node pressure, h_{min} and standard deviation node pressure h_{sd}.

To the purpose of this work, it was not necessary the computation of Protection performances indices provided by SWANP software.

3 Case study and results

The novel algorithm and the new features have been tested on a real water distribution system: the Alcalá de Henares water system, a network of a large town in the Spain, with 202,000 inhabitants, three sources, 11,473 nodes and 12,454 pipes. Specifically, in the Figure 2, the original layout and a water network partitioning in 10 DMAs are provided in novel QGIS framework, in which, with a different colour, each DMA is illustrated.



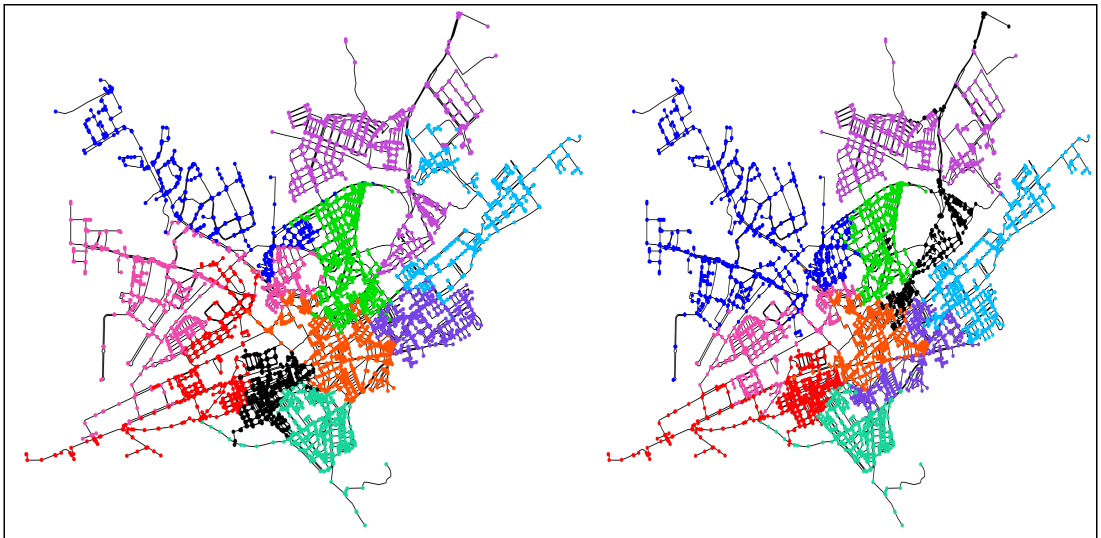

c) d)

Figure 2 Original network a); water network partitioning layouts in SWANP 3.5: b) W1, c) W2 and d) W3

The proposed partitioning layouts of Alcalá de Henares water network were achieved by inserting 15 flow meters on boundary pipes to ensure the hydraulic connection with the sources. To compute the performance indices, a design pressure h^{*}=25 m was employed.
In Table 1 and 2, energy and topological performance indices, obtained with or without weights showing a very good performance with values significantly closer to the original network (resilience deviation indices I_{rd} is ever lower than 20% for all cases). Specifically, the hydraulic performances of partitioning layout, W1 (no-weight), are slightly different from the original network layout, as indicated by a low value of resilience deviation, about 3.6%. Despite the large number of closed pipes, the surplus of energy in layout W1 is very similar to that available in non-partitioning layout, as well as confirmed by the hydraulic performance indices of W1 which are almost equivalent to ones computed for the original network.
Conversely, layout W2, obtained with pipe diameter as weight, shows a resilience deviation more large than other two configurations (I_{rd}=20%), nevertheless in terms of node pressure, the minimum value is slightly greater than other layouts and the maximum is lower than original layout and W1 layout; this solution could represent an advantage for the Water utility in terms of water losses reduction. In other terms, an acceptable decrease of pressure conditions in the water network involves a reduction of water leakage, especially during the hours of lower consumption, and of mechanical stresses for the pipes that means less breaks.

Table 1 Hydraulic and energy Performance Indices

PI	Network	W_1	W_2	W_3
h_{min}	18.57	18.47	18.78	16.10
h_{mean}	47.03	46.26	42.77	44.70
h_{max}	63.98	63.58	60.82	60.32
h_{sd}	8.96	8.86	6.84	8.78
I_r	0.948	0.914	0.760	0.850
I_{rd}	-	3.6	19.8	10.3

Table 2 Topological Performance Indices

PI	Network	W_1	W_2	W_3
n_1	-	1429	906	1140
n_2	-	1047	1238	930
n_3	-	846	805	1598
n_4	-	1432	1438	1139
n_5	-	935	1624	1103
n_6	-	1308	978	782
n_7	-	1633	950	1385
n_8	-	731	1488	1305
n_9	-	1157	998	1097
n_{10}	-	958	1051	997
I_b	-	1.42	1.42	1.39
I_d	-	1.47	1.58	1.24
N_{ec}	-	79	102	100
Q	-	0.887	0.890	0.892
APL	64.87	86.77	103.99	84.64
Δ_{APL}	-	0.25	0.38	0.23

Finally, the layout W3, aimed to balance the water demand among the DMAs, shows an intermediate alteration of hydraulic performance (I_{rd}=10%), but the minimum pressure is lower than the other partitioning layouts. This configuration could be interesting because could support the Water Utility to define the minimum night flow [4], simply comparing the consumptions of each DMAs, and locate areas where focus on searching for water losses.

From a topological point of view, the proposed partitioning layout have different size and dimension, as shown in Figure 1. All studied configurations are unbalanced, the better-balanced layout is W3. Moreover, the low value of demand balance index, I_d=1.24 for W3, shows the effectiveness of proposed pipe-weight (Eq. 3). In this regard, it is worth highlight that FC algorithm does not adopt node-weight, thus the definition of pipe-weight of Eq. 3 was been necessary force the algorithm to obtain DMAs with about the same amount of water supplied.

The modularity metric is always higher than 0.3, for all partitioning layout Q> 0.88 that shows a significant community structure in a network. Anyway, it is worth to highlight the effectiveness of the use of APL deviation that better catch the differences between three case studies. Indeed, for W3 layout, Δ_{APL}=0.23 is the lowest despite the large number of edge cut, N_{ec}=100, while the *APL* deviation of W1 is slightly higher but with a considerable lower number of closed pipe; then W2 increases Δ_{APL} significantly compared to other solutions because the arrangement of edge-cut pipes increases the number of steps of paths between all pairs of nodes.
Finally, since the aim of SWANP is to provide a decision support system, it is possible to compare different partitioning solutions by means of a multi-criteria evaluation carried out plotting a radar diagram where the vertices represent the performance indices, standardized to a unit scale. Specifically, the best solution is the one that covers the widest area of diagram.
For this case study, the radar diagram of Figure 3 was obtained comparing five performance indices: resilience index, minimum pressure, average path length, edge-cut and demand balance index, but the user could choose all other indices computed in SWANP. The analysis of radar diagram reported in Figure 3, allows identifying W1 as the best partitioning layout; in fact, the solution without-weight W1 covers a wide area of the diagram outperforming the other two solutions.

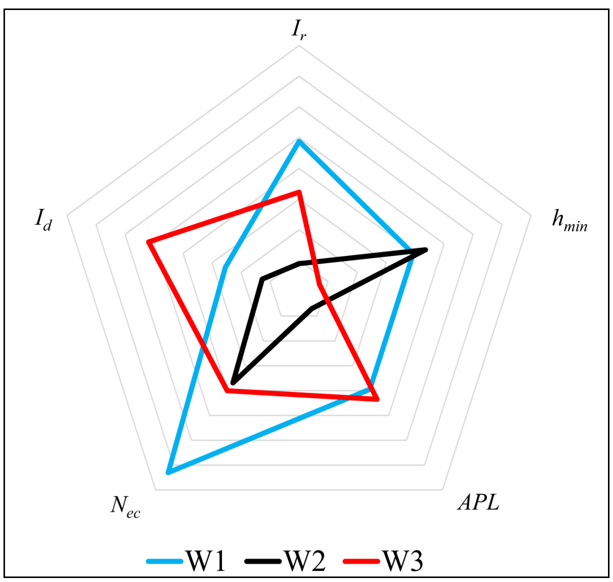


Figure 3 Radar diagram of partitioning layouts

4 Conclusions

The collaboration between the research group of University of Campania, the spinoff MedHydro and the water utility AQUALIA allowed the development and testing of a third release of SWANP 3.5 on a large water network. The software represents an useful tool to carry out advanced performance analysis and to apply "divide and conquer" paradigm defining automatically optimal DMA of water network comparing different solutions with energy and topological performance indices. Specifically, the FG algorithm, already used in the social network analysis, coupled with a genetic algorithm to define heuristically the optimal positioning of flow meters and gate valves, provides an easy way to identify automatically an optimal water network partitioning for a large network with about 12,000 nodes. Finally, SWANP shows possible alternative displays of water distribution network opening novel perspectives for the operators of water utilities.

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