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Water Supply Network Sectorization Based on Social Networks Community Detection Algorithms

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Abstract

Sectorization is a process aimed at efficiently managing Water Supply Networks (WSNs). There are many large WSNs where the number of sectors into which they might be subdivided is initially unknown. Our method uses concepts derived from the Social Network Theory (SNT) such as centrality and community detection to obtain such subdivisions. The output is then evaluated through energy criteria. This methodology entails two very important benefits over other methods previously proposed. Firstly, it is applicable to WSNs depending on a network trunk and, secondly, it considers the technical know-how of the staff of the water utility.

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Keywords: water supply networks; sectorization; social networks, community detection; resilience

1. Introduction

Sectorization is an operational approach currently used by many water utilities, mainly in Europe and Latin America, to have better control over water distribution systems; especially over non revenue water (NRW) related aspects. In recent times, this technique has been implemented in many Latin American urban centers, where water losses are estimated to be of the order of 50% of the water into supply [14]. In sectorized WSNs some pipes are closed to isolate areas or sectors, and for each sector, one feed line is appointed. In the latter a flow meter is allocated to permanently control the inflow.

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Despite its importance, there is a general lack of guidelines on this technique. Most of the implementation cases follow a trial and error approach and also lack follow-up after implementation. The guidance document proposed by [10] is one of the most important and widely known. For the size of the sectors, [10] recommends the use of a wide range of number of connections (500-3000 connections), whereas [6] recommends a wide range of pipe length (4-30 km), depending on the required accuracy for water losses control.

Although sectorization entails several benefits, it also has some remarkable drawbacks: reduction of hydraulic redundancy, which translates into more head losses (due to an increase of friction) and into reduction of the capacity of the network to overcome critical scenarios; negative impact over water quality, which stems from a lowering in water velocity. In general, small sectors deliver more accuracy to detect faults (e.g. a burst). However, they also entail higher investment in the purchase of more valves and flow meters. Large sectors implementation, on the other hand, is expected to be less expensive. However, accuracy to detect faults is reduced. From all the above it can be concluded that a good sectorization layout has to balance the hydraulic, operational an economical aspects of a WSN. Several computer based methods have been put forward in order to create sectorization schemes in WSNs. Most of them have tackled the sectorization problem from a graph partitioning perspective, defining the sectors around one or some few sources [1, 4, 8, 16]. Nevertheless, some networks are dependent on a trunk network and, accordingly, it would be not feasible to exclusively define one or some few sources for each sector. Although there are many cities with this type of layout, only few studies have tackled this problem [2, 3].

Graph clustering is a research branch of major interest due to its very extensive field of applications, including structure analysis in WSNs. In general, it might be classified into two sub-branches: clustering in graphs where the number of subdivisions is *a priori* known and clustering in graphs where such number is initially unknown. The second is better identified as community detection, which stems from social network theory (SNT). This theory studies the relations among individual elements bound by bridge entities. A social network (SN) can be abstracted from any system with inter-related individuals. E.g., friendship among people is depicted as SNs in the web space. A remarkable concept between the SNT is *centrality*, which is a magnitude used to assess the importance of a given element in the network to interconnect two or more nodes. Node and pipe *betweenness* are two well-known measures that allow the quantification of this magnitude. The *betweenness* of a given node or pipe, measures the amount of paths that connect two given nodes and that pass through that node or pipe [11].

There are some algorithms to efficiently compute communities in SNs. In general, they attempt to unveil the graph community structure which maximizes its *modularity* measure. The latter measure represents the fact that there are many edges within each community and only few between them [5, 11]. Specifically, the *Walktrap* algorithm works based upon the idea that random walks throughout the graph tend to detect subgraphs (areas of the graph with high edge density) as there are only few links that lead outside a given community. The approach has several advantages: it captures well the community structure in a network; it can be efficiently computed; and it can be used in agglomerative algorithms to compute efficiently the community structure of the network. Performance comparisons of the method with other similar methods have shown the advantages of this algorithm in terms of results quality and have ranked it among the best methods in terms running time [12]. All merges that are carried out in the community search process that has been earlier described can be represented as a *dendrogram*, which is a graphical structure where each graph node is initially represented as an individual community. As the process advances, the nodes are joined to form new communities. The resulting communities are merged successively until all the nodes form part of a unique community.

As stated above, all systems with interrelated nodes can be represented as a SN and WSNs are not the exception. In this case, the nodes, tanks and reservoir of the WSN correspond to the nodes of the SN, whereas the pipes, valves and pumps are the edges. Once a WSN is abstracted as a SN, the concepts described above can be applied to approach the sectorization problem as a community detection problem.

2. Methodology

This section describes the proposed methodology to sectorize WSNs depending of a trunk network. Firstly, the lines that should not be included in the sectorization (the trunk network) are identified by means of edge *betweenness*, *flow* and *diameter* analysis. As most of the lines have a *betweenness* measurement value over zero, the water utility technical staff should decides the threshold that defines the lines that are part of the trunk and those that are part of the distribution network. This step ends when the trunk network is temporally segregated from the distribution network.

Over the new reduced graph, the *walktrap* algorithm is executed in order to detect the community division with highest modularity. In this point a sector size constraint should be set. If the community layout with highest modularity does not match the size constraint, additional community merging or splitting can be conducted by scaling up or down the output *dendrogram*. Once the communities that meet the size requirement are identified, the process continues to the energy and hydraulic evaluation stage.

The energy and hydraulic assessment is intended to determine which lines are more convenient to be appointed as entrances for each sector. It is carried out by means of two indexes and by means of pressure comparisons. The first of the indexes is the resilience index (I_r) and the second one is the head reduction index (I_{hi}). The I_r, proposed by [15], measures the capacity of a network to overcome pipe failures. It has been used as criterion in previously proposed sectorization methodologies [4]. The second one is an estimation of the index of power reduction (I_{hr}) due to deploying a sectorization layout. Finally, the upper and lower pressure values before and after sectorization implementation are compared. This energy and hydraulic evaluation are carried out in the period of lower pressure (higher demand) given the fact that it is the worst scenario. Ensuring water supply in this period ensures supply the rest of time. The equations used to calculate the indexes earlier mentioned are displayed below.

2.1. The resilience index (Ir)

The total available power (P_t) in the network can be calculated by adding up the power supplied by all tanks and pumps (equation 1).

$$P_t = \frac{\rho \times g \times \left[\left(\sum_{t=1\ldots t}^{t} Q_t \times H_t \right) + \left(\sum_{p=1\ldots p}^{p} Q_p \times H_p \right) \right]}{1000} \quad (1)$$

where:
P_t: Total available power provided by all the sources expressed in *kW*
ρ : Water density corresponding to 1000 *kg/m³*
g : Gravity acceleration expressed in m/s^2
Q_t: Exiting flow from a tank *i* expressed in m^3/s
H_t: Head of a tank *i* expressed in *m m*
Q_P: Flow of pump *i* expressed in m^3/s
H_P: Head of a pump *i* expressed in *m*

The power in the form of pressure that is provided to all nodes (P_n) can be estimated adding up the output of multiplying the total demand at each node and the total head in the same node (equation 2).

$$P_n = \frac{\rho \times g \times \left(\sum_{i=1\ldots n}^{n} Q_i \times H_i \right)}{1000} \quad (2)$$

where:
P_n: Power provided to all nodes as pressure expressed in *kW*
ρ : Water density corresponding to 1000 kg/m^3
g : Gravity acceleration expressed in m/s^2
Q_i: Demand (consumption and leaks) at node *i* expressed in m^3/s
H_i: Head in node *i* expressed in *m*

The value of P_n may be expressed in real terms, when a real head value is used in its calculation. It may also be expressed in theoretical terms, when a required head value is used. As it is shown in equation 3, the required head is calculated by adding up the node elevation and the required pressure value:

$$P_n^{requiered} = \frac{\rho \times g \times \left[\sum_{i=1 \ldots n}^{n} Q_i \times \left(E_i + P_i^{requiered} \right) \right]}{1000} \tag{3}$$

where:
$P_n^{required}$: Power required in all nodes to satisfy a pressure limit expressed in kW
E_i: Elevation of node i expressed in m
$P_i^{required}$: Lower pressure requirement at node i expressed in m

Considering that P_t may be expressed as the sum of P_n and the dissipated power (from now on operational power – P_o –) due to friction, then, the previous one may be calculated by subtracting P_n from P_t (equation 4).

$$P_o = P_t - P_n \tag{4}$$

where:
P_o: Operational power expressed in kW
P_t: Total available power expressed in kW
P_n: Power in all nodes expressed in kW

Depending on the value of P_n used (real o required) in the evaluation of equation 4, its output can be either real or required. Both are then used to evaluate the I_r (equation 5).

$$Ir = 1 - \frac{P_o^{real}}{P_o^{requiered}} \tag{5}$$

2.2. Index of head reduction (Ihr)

The I_r can be used to assess the adequacy of a sectorization layout regarding to a pressure threshold. Nevertheless, a more general evaluation can be carried out by just comparing the reduction of P_n resulting from implementing a given sectorization layout (see equation 6). This approach would be more suitable for networks working under fair conditions, where the minimum pressure reaches very low values.

$$I_{hr} = \left(1 - \frac{\sum_{i=1 \ldots \mathrm{n}}^{n} Q_i^x \times H_i^x}{\sum_{i=1 \ldots \mathrm{n}}^{n} Q_i^0 \times H_i^0} \right) \times 100 \tag{6}$$

where:
I_{hr}: Index of head reduction
Q_i^x: Demand (consumption and leaks) in a node i after sectorization expressed in m^3/s
H_i^x: Head in a node i after sectorization expressed in m
Q_i^0: Demand (consumption and leaks) in node i before sectorization expressed in m^3/s
H_i^0: Head in node i before sectorization expressed in m
Fig. 1 shows the whole process.

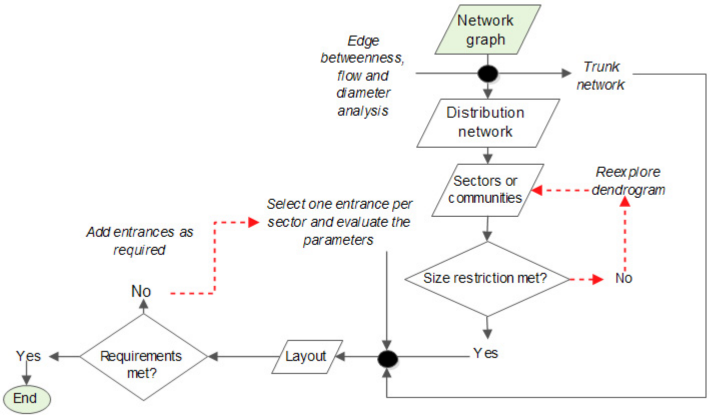

Fig. 1. Flow chart of the whole process

2.3. Implementation examples

The application of the methodology is exemplified in the sectorization of two WSNs. The first one is one of the example networks of the software of hydraulic simulation EPANET [13]. The second one is the network of the Battle of Water networks II (BWN-II) [9].

3. Example network of EPANET

This network is formed by 91 junctions, 2 reservoirs, 3 tanks and 2 pumps. Fig. 2 depicts the process carried out by the methodology to find the outline of sectorization. The output is a network subdivision into five sectors (see Fig. 3). The lower size limit was set at 1500 m and no upper limit was set.

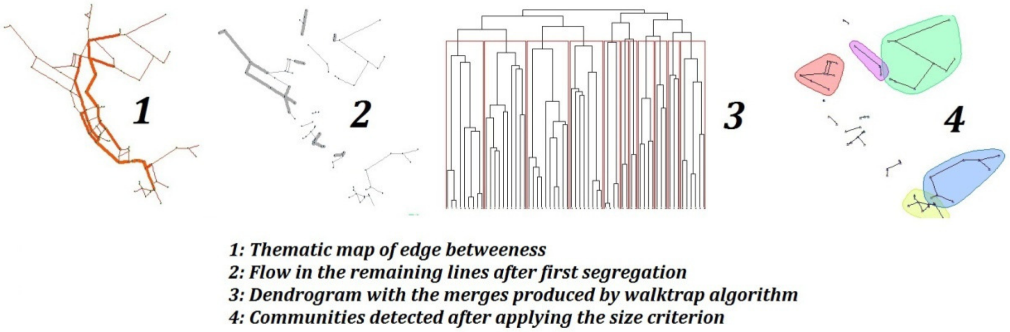

Fig. 2. Sectorization process

Table 1 shows the energy and hydraulic indicator before and after sectorization. It shows how the deployment of the sectorization scheme does not alter drastically neither the energy indicators nor the hydraulic indicators. It is also important to highlight that the same network has been previously used to exemplify a multi-agent based sectorization methodology [7]. In that study the network was subdivided into three sectors. The lake, the river and tank 3 were detached from tank 1 and tank 2. The weakness of that solution steams from the fact that the lake and the river are the only sources of water that feed the tanks, thus detaching them from tank 1 and tank 2 would translate into supply shortage.

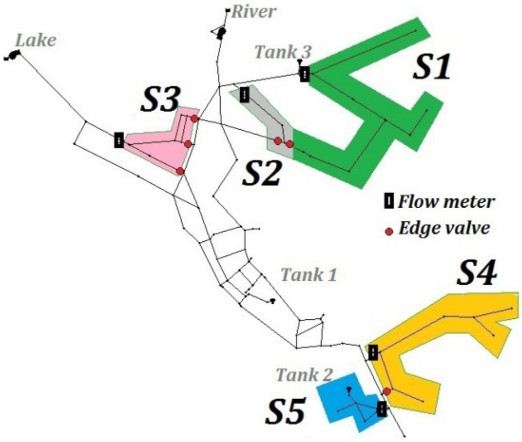

Fig. 3. Output sectorization layout. Network example EPANET

Table 1. Energy and hydraulic indicators. Example Network EPANET

Indicator	Before sectorization	After sectorization
I_r	0.32	0.32
I_{hr}	NA	0.87%
Upper pressure (m)	91.40	91.36
Lower pressure (m)	5.15	5.08
Average pressure (m)	40.54	39.81
Median pressure (m)	40.38	40.00

4. Network BWN-II

This network is formed by 399 junctions, 1 reservoir, 7 tanks and 11 pumps. Using the proposed methodology, 13 sectors where detected, as shown in Fig. 4. The lower size limit was set at 1 km and no upper limit was set. It is worth mentioning that this network relies on five sectors initially predefined. Each of them depends on a single pumping system. However, pump system 1 corresponds to the only source of water for the entire network, therefore delimiting pumping systems 1 as part of sector 1 implies that a flow meter should be placed at the exit of the sector to be able to register the outflow. The proposed methodology, instead, encompasses the segregation of the lines that transport water from the pumping system 1 to the rest of pumping systems. Table 2 shows the energy and hydraulic indicator before and after sectorization. As it occurs in the first example, the sectorization layout implementation does not alter meaningfully the hydraulic and energetic performance of the network.

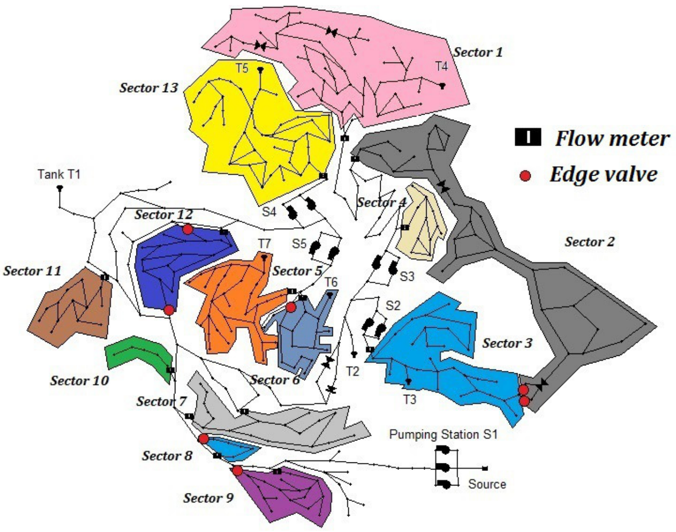

Fig. 4. Output sectorization layout BWN-II

Table 2. Energy and hydraulic indicators. Network BWN-II

Indicator	Before sectorization	After Sectorization
I_r	0.24	0.23
I_{hr}	NA	1.61%
Upper pressure value (m)	98.53	98.27
Lower pressure value (m)	0	0
Average pressure value (m)	38.57	27.03
Median pressure (m)	37.59	26.24

5. Conclusion

This work presents the application of some concepts that stem from the SNT along with hydraulic and energy criteria to tackle the problem of sectorization of WSNs depending of a trunk network. The proposed methodology is based upon the idea that there are some pipes that should not be included in the sectorization scheme because its closure can excessively affect the performance of the network. Also it addresses the problem of determining the number of sectors in those networks where such number is *a priori* unknown. The approach to deal with the latter aspect is based upon concepts of community detection in graphs. As the number of sector layouts that can be found in a WSN may be excessively large, the layout with maximal modularity is used as starting point in the search of the community that best fits the size constraint. Energy and hydraulic criteria are then used to determine their water entrances. This method has three advantages over other sectorization methodologies previously presented. Firstly, sectors are deployed over the distribution network, where physical losses are more frequent. Secondly, as large diameter pipes are not included, the cost of the purchase of flow meters and valves is expected to be lowered. It also facilitates urban-constructive aspects as it is not expected that the smaller diameter pipes are located in the main streets of the city. The methodology has been tested in the sectorization of two WSNs. In the worst case, the deviation of the I_r is 5%. Nevertheless it is important to be aware that these are relatively small networks, thus, it would be important to challenge the methodology in a larger WSNs. In this first attempt, the water utility technical staff is responsible of deciding the scope of the trunk network. Depending on the level of expertise of the technicians, this can be appropriately or wrongly conducted. Accordingly, it would be important to rely on a mechanism to energetically evaluate the alternatives of the trunk network.

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