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A Decision Support Tool for Water Supply System Decentralization via Distribution Network Sectorization

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Abstract: Many water supply systems, conceived to operate in centralized manner, face difficulties to adapt to dynamic changes, such as population growth, city extension, and industrial development. Decentralization of these systems may be an effective solution. Known techniques for distribution network sectorization design can help to achieve such a goal, but this has not been recognized in the literature. None of those known techniques considers the conversion of a centralized system to a decentralized one. In this paper, two new distinct yet complementary methodologies for water supply system decentralization by distribution network sectorization are proposed and implemented in a software decision support tool freely available on internet. The first methodology identifies the main flow paths from water sources to some strategic nodes and considers the nodes in these paths as new potential sources for dividing the rest of the network. The second methodology sectorizes the network according to the contribution of sources to the consumption at nodes, based on mass balance equations for the transport of a hypothetical conservative constituent in a steady state. Both methods were applied to two real network models. The results obtained were better, for decentralizing the supply, compared to those obtained by other methodologies proposed in the literature.

Keywords: decentralized water systems; district metered areas; graph theory search algorithms; water distribution network sectorization; water distribution system

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1. Introduction

Water and energy are essential resources related to the life and economy of any society. The protection and conservation of water is essential because it is a limited resource, and we depend on it. Water security is complex and multi-faceted, due to constant population growth, land use changes, migration to cities, floods, droughts, and other hydrological effects related to the climatic change that affect its availability, quality, and quantity [1]. Faced with these challenges, there is great concern now whether current water supply in its conventional, highly interconnected centralized system form will be able to adequately manage the service in many places around the world [2].

Populations in most countries belonging to the Organization for Economic Cooperation and Development (OECD) enjoy high levels of access to centralized networked systems of water supply and sanitation. However, the maintenance of these systems is becoming more difficult because of the major investments required to repair and replace ageing infrastructure [3]. In contrast, developing countries generally cannot build centralized water supply and sanitation infrastructure for their entire population, due to lack of money in the first place. Faced with this situation, governments around the world, researchers, and private industry are considering new alternatives to supply water, such as grey water reuse and water supply system decentralization, from a technical, socioeconomic, environmental, and institutional perspective, in both OECD and developing nations [4].

Irina Bokova, the former Director-General of United Nations Educational, Scientific and Cultural Organization (UNESCO), in her message on World Water Day (South Africa, 2017), concerning the launch of the World Water Development Report 2017, stated that wastewater can be a reliable alternative source of water, shifting the paradigm of wastewater management from "treatment and disposal" to "reduce, reuse, recycle and resource recovery". The issue of water reuse is growing, and there is now a wide variety of technologies and systems available to meet the needs of emerging economies and OECD countries. In contrast, the provision of water in a decentralized way is less clear: there are debates about the benefits and costs of such options, and there are still doubts about its relevance, even in the context of the OECD countries, mainly because the way of supplying water in many of these countries is based on a centralized infrastructure and a single use of water [3].

A decentralized water system is a group of water subsystems with a certain degree of autonomy from the entire system. According to Bieker et al. [5], future water systems will be more decentralized than conventional ones if the water produced in each subsystem is to be reused. This will reduce the distances between water users and treatment plants. In addition, energy expenditure is minimized, in case of pumping water, as well as infrastructure costs, since water is used close to where it is supplied [6]. In addition, they easily adapt to future changes in the city (such as spatial expansions), providing greater flexibility without affecting the water supply and sanitation to users [7,8], and can be implemented gradually reducing the initial investment costs [9].

Designing a water supply system in a decentralized way also provides other benefits. A decentralized system allows for a better pressure management in the network, which favors leak reduction [10,11], facilitates the detection, localization, and control of anomalies in the supply identifying the areas in which the capital investment would be best used [12,13], carries out water audits, obtains information from areas on the amount of water that is not charged [14,15], and protect the network from possible attacks due to accidental or malicious contamination [16]. At the same time, it reduces distribution network redundancy and, thus, if not properly designed, and done, may affect water supply reliability. The drinking water quality might also be affected in the network sectorization by the possible increase in its residence time in the network due to the closure of some pipes to form the sectors [17]. Urban water distribution systems are traditionally designed as looped pipe systems, where water can arrive to any demand points by alternative flow paths in case of a break in some network pipe or other emergency situations. A good decentralization design should therefore provide the above stated benefits with a minimal impact on the water supply reliability, as opposed to a bad decentralization design that can affect the good operation of the system by making it more vulnerable. [18–20]. In general, decentralizing a water supply system allows for greater control within each independent subsystem and, if some problems exist in the subsystem, such as high leakage or other abnormality, it makes it possible to perform more detailed water audits and analysis, moreover if combined with real-time monitoring and hydraulic network modeling.

The division of water supply systems in district metering areas (DMAs), also named water distribution network sectorization, is a well-known technique for leakage reduction and improving operation control [13] in centralized water supply systems. It can also be an effective mean of water supply decentralization, but this has not been recognized in the scientific literature. Several researchers have proposed methods for water distribution network sectorization design. These methods mostly operate in two phases: grouping and sectorization. In the first phase, the desired number of sectors is set or alternatively an algorithm determines their optimal number, obtaining the boundary pipes that will separate the different sectors. In the second phase, the boundary pipes (to be the flow entry points to each sector, and where flow meters will be located) are determined, while the remaining boundaries should be permanently closed by means of sectioning valves to isolate the sectors from each other. For the partitioning phase, various approaches have been suggested based on network topology and element connectivity [21], modularity [22], community structure [23], spectral matrix methods [24,25], multi-agent simulation methods [26,27], or multilevel partitioning [28]. To locate the flow meters and sectioning valves on the boundary lines identified in the first phase, evolutionary algorithms are the most used optimization methods to achieve one or more objectives subject to certain hydraulic and/or economic limitations. A recent detailed review of the state of the art of such approaches is presented by Bui et al. [29]. None of them considers the conversion of a centralized water supply system to a decentralized one, however, and they are not directly applicable to transforming a centralized water network system to a decentralized one. One of the reasons is that water sources and the transmission network can be shared by different sectors in many of the currently proposed methods, when the objective of decentralization is to separate them.

The following section presents two original and distinct methodologies for water supply decentralization by network sectorization, both implemented in a free software tool, which can help managers make decisions according to suggested proposals concerning the location of the flow meters, local water treatment units (if applicable), and the sectioning valves, while maintaining the water pressure as close as possible to that of the original network model. These two methodologies can be used as mutually complementary for some water supply system configurations, while for other configurations, only one of them would be appropriate. Both of them are based on the hydraulic simulation of the network response, by combining the EPANET hydraulic model [30] with typical graph theory search algorithms. The first one identifies the main flow paths that connect water sources with certain strategic nodes, and considers the nodes in these paths as new potential sources to sectorize the rest of the network. The second methodology is based on a source tracing analysis, in steady state, to decentralize the network, according to the contribution of each source to the consumption at each node. This methodology is also implemented in a second stage of the first method to continue partitioning the network from the nodes of the main paths considered as potential sources. Both methodologies were applied to two cases of real water distribution network models—one in Spain, and the other in Mexico.

The paper is organized as follows. Section 2 first introduces the software EPANET used to run the hydraulic models and emphasizes on some issues to take into account when preparing this model, being followed by a detailed step-by-step description of the two proposed methodologies. Section 3 introduces the two case studies of real network models. Section 4 describes the results and discussions of the application of the proposed methodologies to those case studies. Finally, Section 5 presents our conclusions.

2. Methodologies

2.1. The Network Hydraulic Modelling

The two methodologies proposed in this paper make use of a hydraulic model of the network to be sectorized, for the following purposes:

- To obtain the pipe flows and its direction at a given time (usually the hour of maximum demand), which will be used by the search algorithms.
- To obtain the percentage of the contribution of each water sources to the consumption at each node, which will be used by the second method to separate the sectors by sources, and in the first method to complete the sectorization.
- To check the maximum and minimum pressures at the inner nodes of each sector, depending on the pipes to be closed and the flow entry points for each sectorization proposed.

Water distribution networks can be modeled by demand-driven analysis or pressure-driven analysis. Water demand is assumed to be dependent on the resulting pressure in a pressure-driven analysis, and not dependent on pressure in a demand-driven analysis. Although the flow rate at the end points of consumption is mostly pressure-dependent, when pressure is enough, the users can adjust the flows to their needs, making demand independent of pressure. Given that guarantee a sufficient pressure at all nodes is one the constraints to fulfill by any proposed sectorization at design stage, a demand-driven analysis may be adequate, except for pressure-deficient original networks. On the other hand, although water consumption is actually distributed along the pipes through the service connections, due to the fact that pipes will be included entire in one or another sector, demands can be assumed, lumped at the network nodes for the purposes of sectorization.

Taking these considerations into account, a demand-driven distribution network analysis, with demand lumped at demand nodes, and junctions may be sufficient for our purposes. Such analysis can be done, in principle, with any water distribution network analysis software, e.g., with EPANET. EPANET [30] is a computer software application created by the United States Environmental Protection Agency (EPA), used throughout the world to model water distribution systems. Moreover, it is free, as well as the decision support tools developed by the authors and presented in this paper [31,32]. The original EPANET model was conceived for demand-driven analysis, but some extensions and new versions have been added to it that made it possible to run it in demand-driven mode or pressure driven mode. The simulations in the proposed methodologies can thus be carried out using EPANET in the more precise pressure-driven analysis, especially when the original distribution network is pressure-deficient in some points.

In this way, in what follows, it will be assumed that the user has an operating and duly calibrated hydraulic model in EPANET, on which the simulations will be carried out. Authors recommend the following when preparing the hydraulic model:

- The model should represent all hydraulic elements of the network as they are. That is, if there are two sources of supply (reservoirs or flow injection points) and five tanks, they must be represented exactly in the same way in the model. If it is assumed that tanks are the supply sources, the expected results may not be interpreted correctly.
- The layout of the pipes must be checked and correct (if necessary). This is important to determine the number of flow meters that feed the sectors, and to know their origin when it comes to cascading sectors. To this end, a special additional software tool has been developed by the authors that allows changing pipe orientation if it is found that the flow through these elements is always negative throughout the simulation period. This application is called Reverse-Pipes [31] (see Supplementary Materials Reverse-Pipes) and is freely available from the ResearchGate website of the first author.
- If the layout of the whole network is not fully connected, the different subnetworks separated physically or by closure elements must be previously identified. This will help to better understand the results obtained from the sectorization schemes. With this aim, another tool called iDistricts [32] (see Supplementary Materials iDistricts), was implemented by employing a depth-first graph theory search algorithm, also freely available from ResearchGate for download.

2.2. Search Algorithms

Existing urban water distribution networks generally contain a very large number of components, considering pipes, junctions, demand nodes, tanks, pumps, valves, etc. All of them can by represented as graph structures. Analyzing any sectorization and decentralization approach for such large structures normally requires a large number of repetitive computations, many of them by traversing the entire graph. These computations need to be done in a short time, so that special fast data processing algorithms were needed. Because of that, graph theory and search algorithms, such as the depth-first and breadth-first algorithms [33], along with the Dijkstra's shortest path algorithm [34], were chosen, modified, and implemented as needed for their particular application.

2.3. Method 1. Sectorization by Previously Identifying the Arterial Network

The main pipe or arterial network is first identified in this method. This network comprises the larger diameter pipes that draw and convey water from the water sources. The decentralized water supply subsystems, or sectors, which connect to the arterial network by smaller diameter pipes, are, after that, defined. Normally, each sector is supplied by only one pipe. In this way, besides avoiding installing flow meters in large diameter pipes, thus reducing economic costs, the option of treating water locally at the sector entrance can be proposed and evaluated. Likewise, the formation of cascading sectors is avoided so that the network is more robust against possible breaks in the main pipes if it is included within the sectors. Another advantage of segregating the main pipeline network is the operational flexibility it provides to the system in the face of possible variations in demand, which makes it easier to modify the sectorization scheme. This methodology is executed in eight steps that are described below.

Step 1. Select the start and end points of the paths to build: several researchers have proposed criteria to define the arterial or water transmission pipe network. Campbell [35], Morrison et al. [36], Zhang et al. [37] and Ferrari et al. [38] considered that the arterial network is made up by the larger diameter pipes in the network, but such approach may cause path discontinuity in some network models if there are diameters below a specified threshold. Hajebi et al. [39] proposed a minimum threshold of the circulating flow to be the criteria, but that is only valid if the supply sources feed the network with similar flows, otherwise the set of pipes that transport the flows below the minimum threshold may be excluded from the arterial network. This is the case of water sources strategically located to serve certain areas with a very different demand. Due to these problems, a new approach is proposed here, where the user selects the start and end points for each path. The starting points will be the supply sources (reservoirs and injection points) and the end points will be certain strategic demand nodes.

Step 2. Save the properties of the network model elements: it consists of storing all the information on the properties of the network model elements (length, diameter, elevation, demand, etc.), and the results obtained after running the simulation (flow, flow velocity, line status, pressure, piezometric heads, etc.) for all time intervals of the simulation. In this step, it is also validated if the identifiers of the starting and ending nodes are correct.

Step 3. Associate a weight value to each line of the network model: to find the best path from a start node to an end node, under certain criterion, we need to associate a weight to each pipe in our network model. This weight that can be equal, or related to, the length, diameter, hydraulic resistance, flow, flow velocity, or pressure drop in the pipe, and they are the ones that will be used to analyze the best layouts. If length is associated as such weight, then the shortest path will be sought; if the diameter value is chosen, the path will be made up of the largest diameter pipes. If the hydraulic resistance is chosen, then it is wanted it to be the minimum total one; if it is the flow, flow velocity, or pressure drop, then it is wanted it to be the highest. Pumps and valves are associated with zero weight when length and hydraulic resistance are to be minimized, and with an infinite value if the diameter, flow, flow velocity, or pressure drop is maximized.

Step 4. Determine the lines adjacent to each node: to go through the pipes that will be part of the path, the lines adjacent to each node must first be determined. If the length, diameter, or hydraulic resistance is chosen as weight, we will be faced with an undirected graph, that is, all the lines that connect to a node are adjacent. On the other hand, if the flow, flow velocity or pressure drop is chosen, we will be faced with a directed graph, for which, in each instant of time, we must identify the pipes that introduce flow (inflowing pipes) or receive flow (outflowing pipes) from each node. Likewise, the degree of connectivity of each node of the network model (number of lines linking each node) must be determined.

Step 5. Identify the paths: to identify the paths, given the start and end nodes, a variant of the Dijkstra algorithm [34] was implemented. It is necessary to check first if the start and end node of each path belong to the same hydraulic subsystem, thus avoiding impossible path layouts when the hydraulic model is physically separated one. For this reason, each start and end node must be assigned a numerical identifier of the hydraulic subsystem to which they belong. This preliminary process is carried out by traversing the network from each water source to all the nodes, where when remaining non-visited nodes are found for a water source after the traverse, a new path is started from another source. The depth-first algorithm [33] was implemented to automate this process.

Step 6. Tracing the arterial network: after identifying all the paths by the Dijkstra algorithm, which provides the minimum cost paths from each origin node to all the end nodes, a process of arterial network adaptation is carried out. Starting from the end nodes, each path is navigated upstream until a node that connects three or more pipes identified as part of the traced paths is found. These nodes and pipes that have been navigated will no longer be part of the arterial network. In this way, the arterial network is defined.

Step 7. Identify the hydraulic sectors from the arterial network: to define the sectors, the pipes connecting each node in the backbone network are first identified. Subsequently, from these pipes, the network is traversed applying a depth-first search algorithm. The process ends when all pipes connected to the nodes of the main network have been traversed. If we are dealing with a directed graph, the outflowing pipes will be those through which the flow exits from arterial network nodes.

It should be said that if the arterial network extends a lot, the number of sectors may increase. This will depend on the topological configuration of the network and its connectivity. If we want to segregate the arterial network from the rest of the elements, we must verify that the nodes that link the main pipes are not assigned with a demand, otherwise the demand assignment process must be reviewed. In the software developed by the authors, all the paths, the arterial network, and the identified sectors are stored in a set of shape files that can be viewed from any GIS software.

Step 8. Position flow meters, possible local water treatment points, and sectioning valves for each sector: once all the pipes of each of the sectors that connect to the arterial network have been identified, these are ordered in a decreasing way by its flow, for the period of maximum demand. Initially all the pipes are closed and then are opened one by one. Each pipe opening generates a scenario, for which the maximum and minimum pressure of the entire simulation period is extracted from the EPANET simulator. All these scenarios are stored in a text file to later check which of them meet the pressure conditions of the network. Likewise, for each scenario, two text files are generated, one for flow meters (or possible water treatment points) and the other for sectioning valves. These files are used by the above-mentioned iDistricts tool to view the sectors and the final location of each one of them.

Method 1 is the only one applicable to the cases of networks supplied by only one water source and where it is not feasible to add new sources to supply locally some of the decentralized subsystems. It is still applicable to the cases of networks supplied by a small number of water sources. Method 2, described below, is appropriate for systems supplied by several water sources, or when there exists the option of adding new local water sources inside some of the potential decentralized subsystems.

2.4. Method 2. Sectorization According to the Contribution of the Sources to the Demand at the Nodes

Step 1. Store the properties of the network elements: it consists of saving all the information on the properties of the network model elements (length, diameter, elevation, demand, etc.) and the results obtained after running a simulation (flow, flow velocity, line status, current demand, pressure, etc.), in a custom data structure.

Step 2. Identify the pipes that convey flow to each node: the pipes adjacent to each node and their degree of connectivity must be determined first. Only pipes whose status is open need to be considered. As the network is examined in the direction of flow, it is necessary to determine the inflowing pipes for each node. To do this, the flow velocity and flow rate of each pipe are checked. If the flow velocity is greater than 10^{-6} and the flow is negative, then the upstream node of the pipe is an inflowing node and the downstream node is an outflowing node. If the above condition is not met, then the flow leaves the upstream node and the downstream node receives flow. In the case of pumps and valves, the flow leaves the upstream node, and the downstream node receives flow.

Step 3. Determine the contribution of each source to the consumption at the nodes: the process consists of calculating the concentration of a hypothetical conservative chemical substance at the network nodes, given its concentration at the water supply sources (existing and new proposed sources), under the assumption of constant flow (steady state). If a node i has only one inflowing pipe, its concentration will be equal to the concentration of the upstream node of that pipe, and all pipes that outflow from node i will carry that node's concentration. In the case of a node with several inflowing pipes, its concentration is calculated by Equation (1), where C_{N_i} represents the concentration at node i, T the set of inflowing pipes, Q_p the flow of inflowing pipe p, and C_p concentration in inflowing pipe p.

$$C_{N_i} = \frac{\sum_{p \in T} Q_p C_p}{\sum_{p \in T} Q_p} \quad (1)$$

The algorithm starts at the water supply sources. The first source is selected and stored in a temporal list of pivot nodes (in a stack). From this list of pivot nodes, the first element is extracted, and it is checked if it has inflowing pipes to calculate its concentration by Equation (1). Then, it is checked if the pivot node has outflowing pipes to add the next new pivot node to the list, but under the condition that it has been visited the same number of times as the number of pipes inflowing from each source. This will avoid infinite loops in closed flow paths. The process ends when the list of pivot nodes becomes empty.

Step 4. Assign each node the supply source with the most contribution: after finishing Step 3 above, the contribution percentage of each source to each node will be obtained. These values are ordered from highest to lowest, for each node, and the source with the greatest contribution is assigned to the node. Likewise, each line is assigned a source under the following criteria: if both line ends belong to the same source, then the line assumes the source associated with them. If they belong to different sources then the source assignment is conditioned by the piezometric heads at the end nodes.

Step 5. Source assignment post-processing: after determining the source of water that contributes the most to the consumption at each node, it is possible that some of the nodes become isolated. This may happen for terminal nodes that do not have demand allocation whose only supply pipe can be open or closed, and for a branch of consecutive pipes whose junction nodes have no demand. To assign a water source to these nodes, and to their respective supply pipes, a special routine is implemented where all the pipes that connect to these isolated nodes are stored in a vector. Then, in another vector, the isolated nodes identified for each pipe are stored and the first pivot node is extracted. Starting from this node and traversing the network using the breadth-first algorithm, a node with assigned water source is reached. The set of nodes and pipelines traversed is assigned the identified water source.

Step 6. Identify candidate pipes to close or install flow meters and potential local water treatment: at this stage, a set of candidate pipes is selected where a sectioning valve can be installed, as a first option, or a flow meter (and a water treatment unit, if applicable) if the pipe closure generates negative pressures at certain points of the network model. The candidate pipes are selected under the condition that their two end nodes belong to different water sources. The identified candidate pipes are sorted in decreasing order according to the flow that they convey for a given instant of time. The first scenario results from closing all the candidate pipes in the original model. In the following scenario, the first pipe is opened keeping the rest of the pipes closed. In this way, the pipes are opened sequentially until exhausting all candidate pipes. The number of possible scenarios is thus a function of the number of candidate pipes plus one (for the case when all candidate pipes are closed). For each scenario, a hydraulic simulation of the network model is run, and the maximum and minimum pressures are extracted, as well as the number of flow meters (or water treatment units) and/or sectioning valves, to be compared after that with the rest of the scenarios.

Step 7. Save results: the identifiers of the sources that most contribute to the consumption at the demand nodes are stored in a set of node and line shape files. Likewise, the identifiers of the pipes where a flow meter and/or a sectioning valve are to be installed are stored in text files, separately for each scenario. With these text files and the original network model, the hydraulic sectors and/or districts can be identified with the iDistricts tool [32].

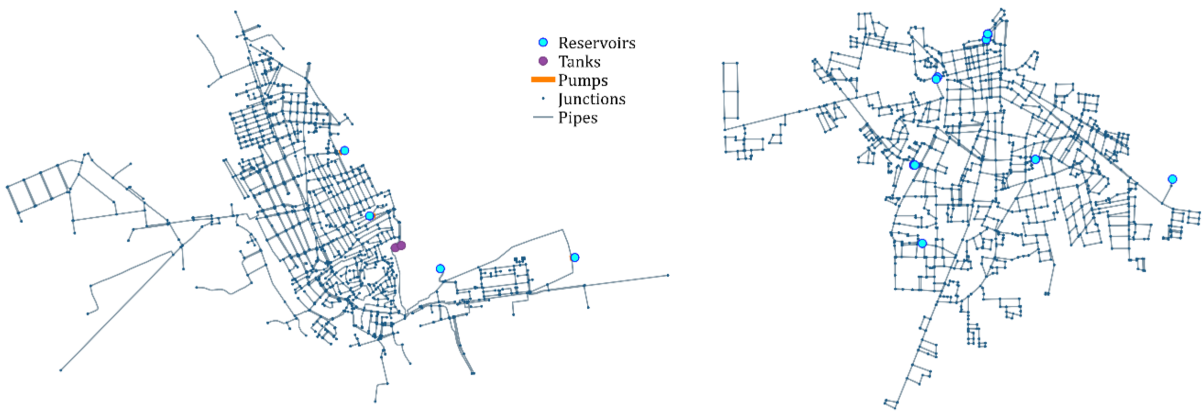
Both methodologies were coded in the Microsoft Visual Studio 2019 programming environment (Visual Basic.Net), and two free libraries were used: shapelib [40] and the

EPANET hydraulic calculation engine [41]. The shapelib library allows to create, write, and read geospatial and alphanumeric information contained in the shapefile (.shp) and table dBASE (.dbf), and the EPANET library was used to read and modify different design and operation network parameters, execute step-by-step extended period simulations, retrieving the results as they were generated, and save the changes to the same file, or for generating another file [42].

3. Case Studies

3.1. Villena Network

Villena is a municipality and a city of the Valencian Community (Spain). It has an irregular area with elevation drop of up to 70 m and is supplied by three water wells (named Fisura, Solana, and La Mina). The La Mina well only comes into operation in an emergency. Another well, the San Francisco well, is also included in the model, but it is currently out of service. The water level of the operating wells is at 370 m above sea level and the flow pumped from the Fisura and Solana wells is 80 and 56 L per second, respectively. The water supply to the network is carried out by direct injection from both wells. From the Fisura well, part of the water is stored in the Cruces II (6000 m^3) and Cruces I (2500 m^3) tanks, which perform the regulation function of the pumping system and provide flow to the network as required by demand (Figure 1a). A summary of how the network is constituted is described as follows [10,43]: 1198 nodes (demand and junction nodes), four reservoirs, two tanks, 1332 pipes, three pumps, control laws, diameter range 20–400 mm (where 52% of them are less than and equal to 100 mm), absolute roughness 0.1–0.3 mm (where 88% of the pipes have roughness equal to 0.2 mm). The network is modeled for a 23 h period.



(**a**) (**b**)

Figure 1. (**a**) Villena network; (**b**) Matamoros network.

3.2. Matamoros Network

The Municipality of Matamoros is located in the northern Gulf Coastal Plain, Tamaulipas state in Mexico, with an average altitude of 10 m above sea level. The Rio Grande River separates this Mexican municipality from the United States of America, and is the main source of supplying water to Matamoros, treated at four water treatment plants. The municipal area is 4634 km^2, which represents 5.8% of the state of Tamaulipas, and its economy is based on agriculture and industry. The climate is semi-arid, with little rainfall during the year. The average temperature for the cold season is from 11 to 21 °C and for the hot season from 25 to 35 °C, and the annual rainfall is 600 to 700 mm. The current city population exceeds 600,000 inhabitants and the number of service connections to the city's water distribution network is about 155,000 connections. The total pipe network length is about 1555 km, with diameters between 50 and 750 mm, made of Polyvinyl chloride

(PVC), asbestos cement, cast iron, and high-density polyethylene pipes. Moreover, 70% of the pipes are less than 20 years old. The transport of water from the water treatment plants to the elevated tanks is carried out by cast iron pipes whose age exceeds 40 years, this being one of the causes for the low pressures in some network points, because of bottlenecks due to the reduction of their hydraulic capacity. This also causes water supply to be intermittent. Likewise, there are a large number of derivations connected to the main pipe network that make the water not reach the most remote network sectors. The network model (Figure 1b) [44,45] comprises nine supply sources (three tanks and six wells), 1280 demand nodes, and 1648 pipes.

4. Results and Discussions

4.1. Villena Network

Villena's water system currently operates centrally, supplying water to the network from its two main sources, the Solana and Fisura wells. The water from those two sources comes to mix at certain points in the network depending on the location, elevation, and demand of the nodes. The original network shows a resilience index [19] (I_r) of 0.452 (with a design pressure of 20 m), a maximum pressure of 72.32 m, mean pressure of 52.42 m, and a minimum pressure of 19.57 m. All input data (flow, velocity, pressure, and piezometric heads) correspond to the period of maximum demand (2:00 p.m.).

The first proposed methodology obtained all the paths from the set of suggested start and end nodes (Figure 2a). Then, the main pipe network (arterial network) was defined by the respective post-processing, identifying 19 sectors (Figure 2b). A total of 16 of them have a single connection to the main network and, thus, are branches. Most of them group only a few nodes. The remaining three sectors have more than four connections to the main network. The largest sector has 24 connections to the main network. The extension of the main network is conditioned by the chosen end nodes; therefore, the number of sectors was conditioned by the main network. Depending on the configuration of the original network, it is possible that the more extensive the main network, the more the number of sectors. Decentralizing the Villena network this way, making the main network independent of the sectors, did not provide the expected results, mainly due to the original configuration of the network, but did provide relevant information on the important pipes of the network through which the highest flows are conducted and distributed to the different areas that were previously unknown. In addition, it provides information about prevention works that can be carried out on the main network to guarantee the water supply. In case of a renewal of the main network, these results can be used to switch to a decentralized water supply system.

The second methodology divides the network into two hydraulic subsystems (Figure 2c) each supplied from its own sources (the Solana and Fisura wells). The results are shown in Table 1, where it is indicated that, by closing seven pipes (Scenario 0), the maximum pressure (189.33 m) is much higher than the maximum pressure in the original model (72.32 m), but if a flow meter is installed in one of the closed pipes, the one that provides the most flow (Scenario 1), the maximum pressure is reduced to 94.56 m and the minimum pressure is increased to 17.83 m. If you want to maintain the pressures of the original model, you must select a scenario whose resulting pressures are the closest. From Scenario 1 to 7, if you choose to install one or more flow meters, there will be a dependence on the supply between the two sectors. Based on the results (Table 1) provided by the tool, the manager can make a decision on which scenario to implement in his network. Table 2 shows the maximum, minimum, and average pressure, the number of nodes, the total length, and the elevation drop of each sector obtained with the iDistricts tool, after assigning the identifiers of the pipes where the flowmeter and sectioning valves should be installed in Scenario 1.

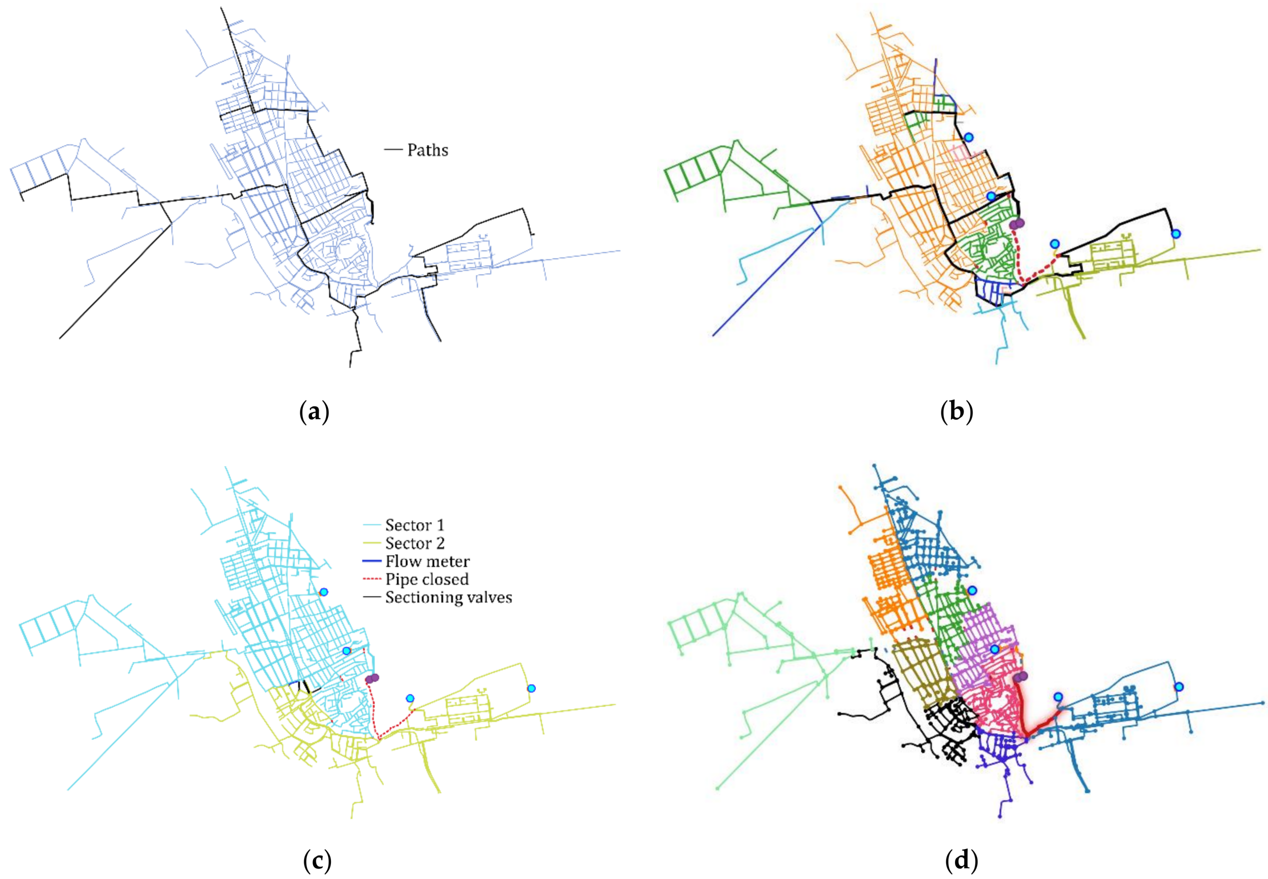


Figure 2. Villena's network sectorization. (**a**) Flow paths, (**b**) sectors by main network, (**c**) sectors by source contributions, (**d**) sectors based on the minimum hydraulic resistance tree.

Table 1. Villena network, maximum, and minimum pressure for each scenario applying the second methodology.

Scenario	Number of Flow Meters	Number of Sect. Valves	Pmax (m)	Pmin (m)	Pmax Node ID	Pmin Node ID
0	0	7	189.33	15.17	J1651	J373
1	1	6	94.56	17.83	J1651	J373
2	2	5	82.54	17.89	J1651	J373
3	3	4	79.35	17.91	J758	J373
4	4	3	78.01	17.92	J758	J373
5	5	2	72.33	17.94	J1651	J373
6	6	1	72.32	17.94	J1651	J373
7	7	0	72.32	17.94	J1651	J373

Table 2. Pressure and other data for each sector.

Sectors	Pmax (m)	Pmean (m)	Pmin (m)	Number of nodes	Total Length (Km)	Elevation Drop (m)
1	70.57	52.27	17.83	610	55.92	49.15
2	94.56	70.51	41.12	236	25.26	28.03

Finally, based on the results of the two methodologies applied to the Villena network, it was decided to incorporate the main network into the sectors, basically because making the main network independent of the sectors did not provide the expected results as explained above. The final number of sectors is 10 (Figure 2d), and the division was obtained by first minimizing the hydraulic resistance tree. The details of this new methodology are not part of the objectives of this work, but it is interesting for future work.

In 2004, some authors participated in the development of two alternative proposals to sectorize Villena's water distribution network, in order to reduce high pressures at certain points in the system. The GISRed [43] extension for ArcView 3.2 was used. Five sectors were identified in the first one of those proposals and sight sectors in the second. The method implemented in GISRed was based on the minimum hydraulic resistance spanning tree topology of the network and a maximum number of connections per sector, with the restrictions of maximum pressure and a single input per sector [10]. In contrast, the main objective of the methodologies proposed in this paper is to decentralize the supply and distribution of water, either by separating the water sources or by creating an arterial network that allows differentiating the inputs to each sector, avoiding dependence between them. Pressure control, by limiting maximum or minimum pressures inside the sectors can still be carried out, as a secondary objective, employing any of the procedures reviewed in the literature. Furthermore, the two proposed methodologies make it possible to determine the number of inputs necessary to meet the minimum pressure restrictions, without forcing it to have to be unique, this being another distinct advantage of the proposed methods.

4.2. Matamoros Network

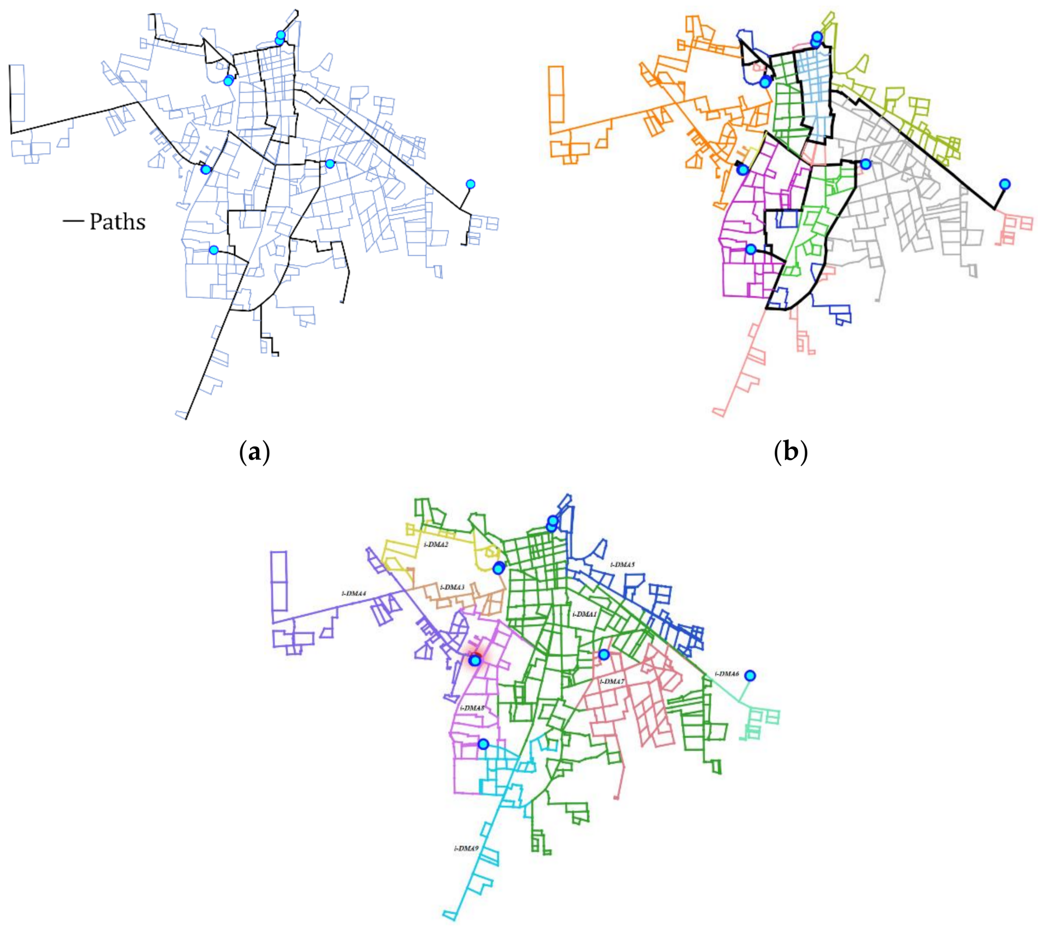
Water supply in the Matamoros model is made from three tanks and six pumps. It is an interconnected network, where water from the sources is mixed in certain points in the network. It currently operates centrally and the objective is to study possible solutions to divide the network by the two proposed methodologies. The original network exhibits a resilience index [19] (I_r) of 0.439 (with a design pressure of 12 m), and a maximum pressure of 31.34 m, mean pressure of 17.46 m, and a minimum pressure of 2.93 m.

A division in 24 sectors was first obtained (Figure 3b), after identifying the arterial network by the paths generated from the set of start and end nodes (Figure 3a). Six of those sectors were larger, with between 10 and 20 connections to the main network, and 18 sectors were smaller size ones with between one and six connections to the same main network. It was found that in three of the sectors, the water flow enters the sector, satisfying its water demand, and returns to the main network. This could be one of the causes of the low pressure in certain parts of the network, due to the fact that the water loses much more pressure in the sector's distribution network whose pipes are smaller in diameter. A total of 123 connections to the main network were obtained. Assigning flow meters and sectioning valves according to that network configuration is thus not economically feasible. In the event that the main network requires renewal because of its age; however, this analysis provides an opportunity to review the flow trajectory and explore new alternative paths that allow decentralizing the supply system.

The application of the second methodology divided the network into nine hydraulic subsystems. The largest of them, according to Figure 3c, shares flow with contiguous sectors because it is the source that provides the most flow to the system. At the exit of said sector, nine flow meters must be installed to contribute to the demand of five contiguous sectors. Moreover, three other sectors need input from other sources to match the pressure of the original network model. In total, 12 flow meters and 26 sectioning valves are needed to divide the network into those nine hydraulic subsystems.

It should be noted that the same number of sectors was obtained previously in [44] by a totally different approach. Independently, Di Nardo et al. [45] examined the same network for different number of sectors (from 2 to 16 sectors), with a much more involved simultaneous cost and energy optimization technique, obtaining the same number of nine sectors as the optimal one.

As a limitation, it is likely that this methodology will identify small sectors that can be merged with other contiguous sectors. In this way, the number of sectioning valves and/or flow meters can be reduced. This stage is not yet implemented in the developed free software tool, but it will be incorporated in the future.



(c)

Figure 3. Matamoros network sectorization. (**a**) Flow paths. (**b**) Sectors by main network. (**c**) Sectors by source contributions.

4.3. Limitations of the Proposed Methodologies and Precautions in Their Use

4.3.1. Arterial Network Method

Declaring an excessive number of strategic points, and consequently paths to be part of the arterial network, may lead to redundant loops and paths. An arterial network that is too extensive may furthermore increase unnecessarily the number of connections and sectors, by creating too many barriers between them.

On the contrary, the declaration of too few strategic points, and therefore paths in the arterial network, can lead to close important pipelines, which would become part of the sectors, thus reducing the transport capacity of the network, or alternately to locate costly large diameter flow meters in them, which will also offer low precision for leaks detection.

Therefore, there is no a priori an optimal number of strategic points for exactly define the arterial network, and its final layout is left to the decision of the user. Thus, the procedures described within the first method constitutes only a decision-making aid tool.

Furthermore, in any case, it is necessary to ensure that the nodes of the arterial network do not have any assigned consumption, since the objective of sectorization is to group all the consumption nodes within the sectors. In this case, these demands would have to be transferred to other nearby nodes, outside the arterial network.

4.3.2. Supply Sources Contribution Method

Care must be taken when identifying the actual supply sources. The direct water supply to the network from a water treatment plant, a borehole, or a lagoon clearly constitute well-differentiated supply points. However, more care must be taken with tanks. A regulating tank can be fed from the transmission lines and supply water to a nearby area. As long as the flow inlets and outlets are well differentiated, and by ensuring that the flow entry is not affected by pipe closures, it is possible to treat those tanks as independent supply sources for sectorization purposes. However, a flow balance tank that is filled from the network in the hours of low consumption (usually at night) and then returns the accumulated volume in the hours of greater consumption (usually in the morning) should not be considered as a supply point at all, since it cannot be isolated from the nearby distribution network on which its filling depends.

5. Conclusions

Water in the world is increasingly scarce; thus, countries that already suffer from this scarcity are looking for new alternatives, such as its reuse and the transformation of centralized water systems to decentralized ones. In this paper, two novel methodologies for water distribution network sectorization design, based on graph theory search algorithms, mass balance of a hypothetical conservative substance at network nodes, and the EPANET hydraulic model, are proposed. These methods, implemented in two free software applications, can be of great help to planners in deciding whether decentralizing a water network system is more economically and technically beneficial, by separating the main network from the rest of the sectors or dividing the network by the number of water sources (or a combination of them). Such sectorization also allows wastewater generated in each sector to be treated locally and reused for its different uses. In this way, environmental sustainability is increased throughout the water cycle, and the network can more easily adapt to future changes.

Decentralizing a water supply system by dividing the water distribution network into small separate sectors is not an easy task, for reasons explained in the introduction section of this paper. In large existing urban water supply systems, the number of possible decentralization layouts is enormous, and the decentralization design must provide the desired decentralization with a minimal impact on the water supply reliability and water quality, subject to hydraulic, cost, and other restrictions. Known methods for DMA water distribution network sectorization do not consider the conversion of a centralized water supply system to a decentralized one. Specific tools, such as the ones described in this paper, are needed to help planners make the best decision. The methodologies for water supply decentralization by network sectorization proposed in this paper have been implemented in a free software tool and can be readily integrated on any Geographic Information System (GIS) software, where, with a cartographic map of the city, users can work directly on the network model, changing the diameter of some pipes or adding new paths that facilitate the grouping of elements into decentralized water demand sectors, helping managers to make decisions about the required number of flow meters, local water treatment units, and sectioning valves.

Supplementary Materials: The following related software developed by the authors is freely available from: iDistricts. A tool to propose or identify hydraulic sectors: https://bit.ly/3j1i3nB. CheckPressure. Herramienta para evaluar las presiones en múltiples escenarios de Epanet: https://bit.ly/37jqkho. Reverse-Pipes. Herramienta para cambiar la orientación de tuberías en modelos de Epanet: http://bit.ly/2KdoN20.

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