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# Water Supply Network Partitioning Based on Simultaneous Cost and Energy Optimization

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**Abstract**

Water Network Partitioning (WNP) improves water network management, simplifying the computation of water budgets and, consequently, allowing the identification and reduction of water loss. It is achieved by inserting flow meters and gate valves in the network, previously clustered in subsystems. The clustering and partitioning phases are carried out with different procedures. The first one requires clustering algorithms that assign network nodes to each district (or cluster). The second one chooses the boundary pipes where flow meters or gate valves are to be inserted. In this paper, SWANP software is employed to achieve a network clustering through two different algorithms based on a multilevel-recursive bisection and community-structure procedures. After that, a novel multi-objective function is introduced and applied to a large Mexican network integrating both cost and energy performance, thus providing a smart Decision Support System (DSS) based on qualitative and quantitative measures, and diagrams for evaluating the optimal layout in terms of the number of districts, cost, and hydraulic performance.

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*Keywords:* Water network partitioning; multi-objective optimization; resilience; graph partitioning; SWANP

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## 1. Introduction

In recent years, the scientific community has shown a surge of interest in networks and their properties, including the Internet, transportation networks, food webs, as well as social and biochemical networks. One property that attracted particular attention is their “community structure”; the division of network nodes into groups within which the network connections are dense, although the groups themselves are sparse. The ability to find and analyse such groups can provide invaluable help in understanding and visualising the structure and behaviour of networks. More recently, this approach has been adopted to divide water distribution systems (WDS) in DMAs as advised by the International Water Association [1]. The layout of the WDS is typically looped, having multiple flow paths from its water sources to the users. This feature of the WDS grants the system a high level of reliability in case of mechanical failures (e.g. pipe breaks, valve malfunction), on the other hand, it makes water-loss control difficult.

For this reason, several methods for re-designing the existing WDS into sub-zones were suggested in the last years. Divide-and-conquer in a water distribution system was introduced in 1980 in the UK [2], [3], essentially, to simplify the localization of water losses and the pressure-management techniques [2]. According to Kunkel [4], up to 85% of the measured leakage in the UK has been eliminated in a national-water-loss-control program based on DMAs through the continuous monitoring of water flows entering each DMA. This also results in an improved capacity for assessing the current level of water leakage in every area of the network [5] so the partitioning of the WDS into DMAs is crucial for identifying the most vulnerable areas [1]. The core goal is to achieve better control over the distribution of water [6], but there are further benefits for partitioning a WDS: enhanced leakage and burst detection and management, a capacity to provide different pressure levels which helps in the establishment of a permanent pressure control system (pressure zones) and enhanced rehabilitation and work planning. In recent years, the combination of sectorization with the use of Pressure Reducing Valves has been investigated, as it can boost the efficiency of the pressure regulation provided by these devices [7]. Partitioning itself, however, can be considered as a pressure-management technique [8], as pipe closures produce significant pressure drops and thus mitigate the background leakage. Recently, water network partitioning techniques have been proposed to protect the network water quality against accidental or malicious contamination [9], [10] using innovative, quality sensors [11] and parameter-estimation techniques [12].

The division of network nodes into groups with required features (i.e., density, balancing, boundary edge minimisation, size limit, etc.) can be achieved only with an optimisation approach because the number of possible DMA layouts is huge. Many approaches are available in scientific and technical literature which vary from empiric trial and error procedures [9] to sophisticated, automated tools integrating network analysis, graph and network theory, as well as optimization methods [2], [3]. The procedures are generally subdivided in two phases [13], [14]: 1) the clustering, aimed at defining the shape and the dimension of the network subsets based on different procedures intended to minimise the edge-cut number and balance the number of nodes for each district, using graph algorithms [15], [16], [17], [18], multilevel partitioning [19], community structure [13], [20], and spectral approach [21]; 2) the physical partitioning, that is the selection of pipes in which to insert flow meters or gate valves, based on iterative [17] or optimization algorithms [18], with the objective of defining the optimal layout that minimises the investment and hydraulics deterioration [5].

In this paper, the second phase of the definition of the optimal layout of DMAs, physical partitioning, is investigated in specific reference to the cost issues coupled to hydraulic performance. This interaction is yet not well studied. Some procedures that find the optimal WNP for user service level compliance and cost minimisation have been proposed [5], this approach, nevertheless, has the following shortcomings: i) the applicability is for small networks only, ii) the number of DMAs is not assigned as input, so it is impossible to have different, best solutions to choose from.

This work, tested on a large Mexican water network, uses SWANP 2.0 software [2], [22] for the clustering phase, and presents a novel multi-objective function that integrates both cost and energy performance. It provides a smart Decision Support System (DSS), based on qualitative and quantitative measures, and diagrams for evaluating the optimal layout in terms of number of DMAs, cost and hydraulic performance.

## 2. Methodology

The proposed methodology is illustrated in Fig. 1 where the main steps to obtain the DSS diagrams so water utility operators are able to choose the best layout of DMAs are summarized.

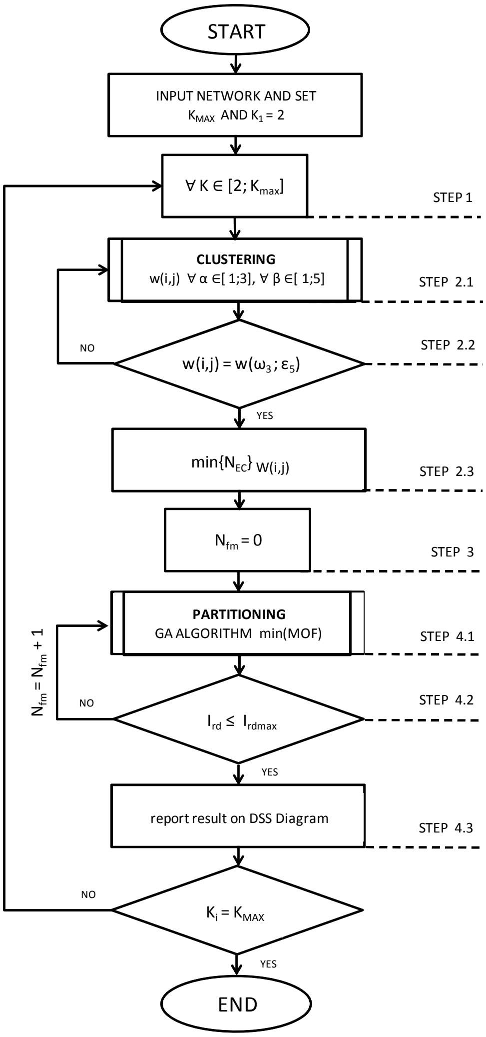

Fig. 1. Flow chart of the proposed methodology to obtain DSS diagram

At STEP 1, the topologic and hydraulic characteristics of the network are provided to SWANP software: the maximum number of DMAs ($k_{max}$), the initial number of districts $k_1$=2, and the maximum resilience deviation $I_{rdmax}$, that have to be set according to [1] and [17]. STEP 2 consists of clustering the water network in the $k_i$ sub-zones (or clusters) using the different algorithms [22], [12] and the weight combinations [2] on both the nodes and the edges in order to minimise the total number of edge-cuts $N_{ec}$ (or boundary pipes) between clusters. Indeed the water 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 indicated respectively with $\omega_{\alpha i}$ (e.g. demand, elevation, etc.), for $i$=1..$n$, or with $\varepsilon_{\beta l}$ (length, diameter, flow, dissipated power, etc.), for $l$=1..$m$.

Network (or graph) clustering consists in defining $k$ clusters (or network subsets) where each node $i \in V$ belongs uniquely to one of the clusters $k_1$, $k_2$, ..., $k_{max}$ such that $k_i \cap k_j = 0$, for $i \neq j$, and $\cup_i k_i = V$. At first, STEP 2.1, it is necessary to define the weight matrix $W$, reported in Table 1, where each element $w(i,j)$ is a vertex-edge weight combination of ($\omega_\alpha$,$\varepsilon_\beta$) applied on all network nodes and pipes. Recently, graph partitioning algorithms and community structures approaches have been applied to the water network clustering problem [13]. In this paper, two procedures developed by the authors (based on graph partitioning algorithms and on community structures approaches), were used: in particular, *Multi-Level Recursive Bisection* (MLRB) [22] with the following weights with $\alpha$=1...2 and $\beta$=1..5 ($\omega_1$=No weight, $\omega_2$=Demand, $\varepsilon_1$= No weight, $\varepsilon_2$=Flow, $\varepsilon_3$= Diameter, $\varepsilon_4$=Length and $\varepsilon_5$=Dissipated Power), and *Edge Betweenness Community* (EBC) [12], with the following weights $\alpha$=3 and $\beta$=1..5 ($\omega_3$=No weight, $\varepsilon_1$=No weight, $\varepsilon_2$=Flow, $\varepsilon_3$= Diameter, $\varepsilon_4$=Length and $\varepsilon_5$=Dissipated Power). For example, as shown in Table 1, a weight combination that belongs to the $W$ matrix is the element $w(2,3)=(\omega_2,\varepsilon_3)$=(Demand, Diameter) solved with MLRB algorithm by assigning the demand to each *i*-th node and the diameter to each *j-th* pipe. Some weights can be imposed from topologic and hydraulic data, others can be computed by a hydraulic simulator as EPANET 2.0 [23].

Table 1. Weight matrix W composed of vertex-edge weight combinations $\omega_\alpha$ and $\varepsilon_\beta$

| | | $\varepsilon_{1j}$ (no weight) | $\varepsilon_{2j}$ (flow) | $\varepsilon_{3j}$ (diameter) | $\varepsilon_{4j}$ (length) | $\varepsilon_{5j}$ (power) |
|---|---|---|---|---|---|---|
| MLRB | $\omega_{1i}$ (no weight) | w(1,1) | w(1,2) | w(1,3) | w(1,4) | w(1,5) |
| | $\omega_{2i}$ (demand) | w(2,1) | w(2,2) | w(2,3) | w(2,4) | w(2,5) |
| EBC | $\omega_{3i}$ (no weight) | w(3,1) | w(3,2) | w(3,3) | w(3,4) | w(3,5) |

In the STEP 2.1-STEP 2.3 cycle, in order to find the optimal layout with minimum number of edge-cuts on boundaries pipes between clusters $min\{N_{ec}\}$, SWANP analyses all weights combinations of the matrix $W$, with two clustering algorithm, in particular: 10 weights combinations (from $w(1,1)$ to $w(2,5)$) with MLRB and 5 weight combinations (from $w(3,1)$ to $w(3,5)$) with EBC, as shown in Table 1. This optimal layout, obtained with the clustering phase, is the starting point for the subsequent network partitioning phase (STEP 4.1), in which the optimal positioning of boundary (or gate) valves $N_{bv}$ and flow meters $N_{fm}=(N_{ec}-N_{bv})$ is found miniminzing a constrained MultiObjective Function (MOF) expressed by the following mathematical expression:

$$MOF = \left( \sum_{j=1}^{N_{fm}} C_{fm} + \sum_{j=1}^{N_{bv}} C_{bv,j} \right) + \left( \gamma \sum_{j=1}^{n} Q_j h_j \right) \tag{1}$$

where $C_{fm,i}$ is the unit cost of the flow-meters and $C_{bv,j}$ is the unit cost of the gate valves, both dependent on the pipe diameter where they will be installed, and $Q_i$ and $h_i$ are the water demand and pressure, respectively, at each network node, with $\gamma$ the specific weight of water. This approach is known as the "weighted-sum" or "scalarization" method [24] that represents a new optimization problem with a unique objective function composed by two functions reported in brackets. The MOF is constrained by the following expression, which imposes a maximum resilience deviation index $I_{rdmax}$ [2], that must not be exceeded:

$$constraint = \left( I_{rd} \le I_{rd\max} \right) \tag{2}$$

Further, the partitioning algorithm tries to minimise the MOF (1) by inserting the minimum number of flow meters because this way the water network partitioning is more effective in achieving the water budget and pressure control [2]. In other words, starting from the initial solution with $N_{fm}$=0 that is all the gate valves inserted in all the edge-cut pipes (STEP 3), thereby achieving a water network sectorization [3], if the constraint is not fulfilled in STEP 4.2, it assigns $N_{fm}$=1 and tries to find the optimal solution for compliance with constraint. If no solution with $N_{fm}$=1 can be found, the partitioning algorithm repeats the procedure increasing by one the number of flow meters until the optimal positioning of the gate valves and the flow meters is found for each node in compliance with the maximum deviation resilience index. The partitioning algorithm required an optimization procedure to find the optimal solution. Indeed, the number of possible combinations, $N_{ck}$, where it is possible to insert flow meters and gate valves in boundary pipes of the water network does not allow for investigating all solutions. In this paper, a Genetic Algorithm (GA) is adopted to find the optimal solution in the cases in which the number of possible solutions was huge [2] with the novel MOF (1). In STEP 4.3, for each $k_i$, the proposed procedure provides simulation results in terms of: a) network partitioning layout with the optimal positioning of the boundary valves and the flow meters; b) the optimal cost illustrated in a DSS diagram. Finally, once the DSS diagram is completed, and the maximum available budget are $C_{max}$, is set, the operator can choose the optimal district layout. In this way, the proposed procedure offers a heuristic methodology to find the optimal solution for the arduous problem of finding a water network partitioning with a user friendly approach that is based on simple-decision-support-system diagrams.

## 3. Results

The procedure was tested on the large network of Matamoros city in Mexico [10] with a number of service connections of about 120,000 and approximately 500,000 city inhabitants. The only water supply source is the Rio Grande River. Water is taken from the river at two points. There are $r$=9 reservoirs. The city is located in the northeast part of the state of Tamaulipas, Mexico. The climate is semi-dry, with hot summers and cold winters (the temperature ranges from -7 to 40° C) and the average annual precipitation is 687.2 mm. The main characteristics of the Matamoros water distribution network model are reported in Table 2 and in Table 3. The design pressure $h_{min}$ for Matamoros is 12 m, but, just in the original network before partitioning, some nodes show water pressure lower than 3 m (corresponding to the service level in different areas with only one floor buildings). The constraint (2) is referred to the maximum resilience deviation index $I_{rdmax}$, set to 25%. Hydraulic simulations were carried out during periods of peak water demand, the worst condition for the Mexican networks as typically they are not designed for fire-fighting conditions (they are actually not equipped with any fire hydrants).

Table 2. Main topological characteristics of the Matamoros network

| Nodes n (-) | Links m (-) | Reservoirs r (-) | Length L (Km) | Pipe materials (-) |
|---|---|---|---|---|
| 1283 | 1651 | 9 | 376.6 | PVC/AC |

Table 3. Main hydraulic characteristics of the Matamoros network

| Average demand $Q_m$ ($m^3/s$) | Peak demand $Q_p$ ($m^3/s$) | Design pressure $h_{min}$ (m) | Resilience deviation $I_{rdmax}$ (-) |
|---|---|---|---|
| 0.987 | 1.342 | 12 | 25% |

Further, a wide cost analysis of gate valves and flow meters was achieved and summarised in Table 4 in which the average cost of each device is reported in function of the pipe diameter. The flow chart in Figure 1 shows that the proposed procedure allows for obtaining a DSS diagram with each optimal solution, in both clustering and partitioning terms, corresponding to each number of DMAs $k$ starting from the simulation results summarised in Table 5. For each clustering layout, the following data was reported: the number of DMAs $k$, the number of *flow meter-gate valves* combinations, the edge-cuts, the sum of the diameters of all edge-cuts $DT_{ec}$, the number of flow meters $N_{fm}$, and gate valves $N_{bv}$, the total costs of devices $C_{tot}$, the total delivered power $P_N$, the value of MOF, the mean $h_{mean}$ and minimum $h_{min}$ pressure, the resilience $I_r$ and resilience deviation $I_{rd}$. Specifically, from $k=2$ to $k=6$, the combinations, $N_{ck}$, are relatively few and it was possible to find the best solutions that directly minimize MOF (1). While from $k=7$ DMAs to $k=15$, the number of possible combinations $N_{ck}$ (from $N_{c7}$=1,560,780 to $N_{c15}$=1.56E+18) does not allow for a complete enumeration of all the combinations, and an optimal (but not best) solution with GA is found. In the Fig. 2, the DSS diagram of the Matamoros network is illustrated for $k=2$ to $k=15$. It is worth to highlight that, for each clustering layout, the number of nodes with a pressure lower than $h_{min}$ is a dozen and they are the same ones that just in the original network before partitioning had water pressure lower than 3 m.

From the $k$=6 DMAs solutions above, the trend shown in Fig. 2 became less *uniform* in terms of cost. This result depends essentially on two reasons: a) the solutions are optimal (and not the best); b) the clustering phase, as already highlighted in a previous study [25], can provide DMA layouts not optimal for the subsequent partitioning phase above all in the case with many water sources.

Table 4. Unit costs of devices in function of pipe diameter

| Pipe diameter (*mm*) | Flow meter cost (*€*) | Gate valve cost (*€*) | Pipe diameter (*mm*) | Flow meter cost (*€*) | Gate valve cost (*€*) |
|---|---|---|---|---|---|
| 50 | 1,974 | 520 | 350 | 5,652 | 3,242 |
| 65 | 2,073 | 560 | 400 | 6,282 | 4,412 |
| 80 | 2,073 | 592 | 450 | 6,726 | 5,964 |

| | | | | | |
|---|---|---|---|---|---|
| 100 | 2,187 | 676 | 500 | 7,125 | 9,122 |
| 125 | 2,325 | 784 | 600 | 8,265 | 11,406 |
| 150 | 2,586 | 940 | 700 | 10,599 | 15,578 |
| 200 | 2,970 | 1,232 | 800 | 12,909 | 21,177 |
| 250 | 3,990 | 1,792 | 900 | 16,011 | 27,198 |
| 300 | 5,109 | 2,228 | 1000 | 19,353 | 33,989 |

Table 5. Matamoros simulation results for *k*=1 to *k*=15 DMAs

| k | $N_{ck}$ (-) | $N_{ec}$ (-) | $DT_{ec}$ (-) | $N_{fm}$ (-) | $N_{bv}$ (-) | $C_{tot}$ (€) | $P_N$ (W) | MOF (-) | $h_{mean}$ (m) | $h_{min}$ (m) | $I_r$ (-) | $I_{rd}$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | - | - | - | - | - | - | 24569 | 24569 | 17.48 | 2.93 | 0.44 | 0.0 |
| 2 | 1 | 6 | 2102 | 0 | 6 | 31301 | 24395 | 55696 | 17.30 | 2.93 | 0.42 | 3.4 |
| 3 | 364 | 14 | 4268 | 3 | 11 | 49626 | 24422 | 74049 | 17.28 | 2.21 | 0.43 | 2.1 |
| 4 | 3060 | 18 | 5486 | 4 | 14 | 70531 | 23356 | 93887 | 16.59 | 1.61 | 0.33 | 25.0 |
| 5 | 38760 | 20 | 6018 | 6 | 14 | 74389 | 23477 | 97866 | 16.63 | 2.03 | 0.33 | 23.6 |
| 6 | 735471 | 24 | 7203 | 8 | 16 | 93060 | 23803 | 116862 | 16.92 | 1.48 | 0.37 | 15.9 |
| 7 | 1560780 | 29 | 8977 | 7 | 22 | 125166 | 23679 | 148845 | 16.79 | 0.61 | 0.36 | 17.0 |
| 8 | 225792840 | 32 | 9213 | 12 | 20 | 117939 | 23690 | 141628 | 16.78 | 1.32 | 0.36 | 17.9 |
| 9 | 92561040 | 33 | 9365 | 10 | 23 | 106487 | 23398 | 129886 | 16.51 | 1.47 | 0.34 | 22.8 |
| 10 | 5.42E+13 | 38 | 10607 | 13 | 25 | 117851 | 23621 | 141472 | 16.70 | 0.80 | 0.34 | 22.3 |
| 11 | 2.51E+14 | 39 | 10987 | 15 | 24 | 125323 | 23688 | 149011 | 16.73 | 0.81 | 0,37 | 14.6 |
| 12 | 1.03E+15 | 41 | 11367 | 16 | 25 | 129063 | 23622 | 152685 | 16.77 | 1.12 | 0,37 | 15.4 |
| 13 | 2.55E+15 | 42 | 11967 | 17 | 25 | 161336 | 23782 | 185119 | 16.84 | 1.17 | 0.39 | 11.5 |
| 14 | 1.72E+16 | 45 | 12685 | 18 | 27 | 145612 | 23748 | 169360 | 16.94 | 1.19 | 0,35 | 19.2 |
| 15 | 1.56E+18 | 51 | 14835 | 22 | 29 | 173985 | 23857 | 197842 | 16.96 | 1.35 | 0.36 | 17.5 |

Indeed in the latter case, the clustering should take into account the hydraulic characteristics of the network with a more accurate assignment of nodes to each source, thereby minimising the path length or dissipated power [25]. Anyway, the optimal solutions found in this study can be widely satisfactory for the water utility because each of them is in compliance with the maximum resilience deviation chosen. The partitioning phase, as highlighted in Table 4, produces a slight decrease of the mean pressure, hmean, essentially equal to that of the original network, but a more consistent worsening of hmin, although limited only to some nodes Nnmin. This result is worsened by the very low values of water pressure in some zones of the original network that presents some critical hydraulic performance. Finally, once defined, the DSS diagram – fixing the maximum budget Cmax – it is possible to identify the optimal clustering (nodes assigned to each DMA) and partitioning (boundary pipes assigned to flow meters or gate valves) in compliance with the given budget.

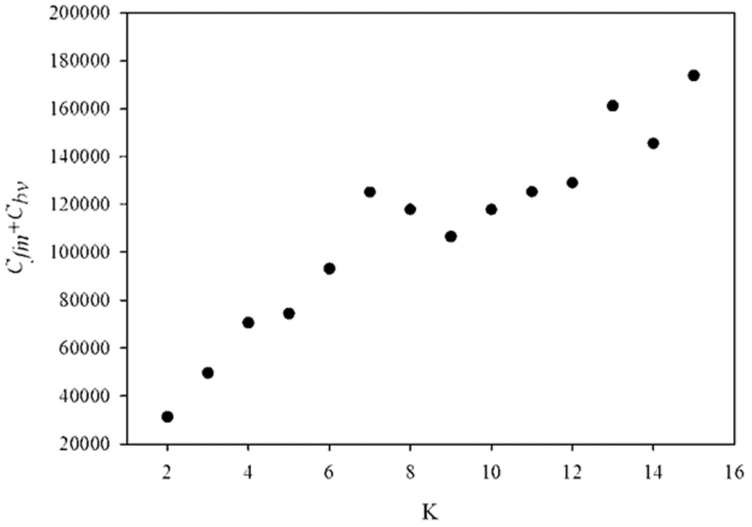

Fig. 2. Decision Support System (DSS) diagram to choose the optimal WNP for Matamoros

Fig. 3 illustrates the partitioning of the Matamoros network, obtained with the constraint of a maximum budget lower than $C_{max}$=125000 euros and with k=9 DMAs equal to the number of water sources.

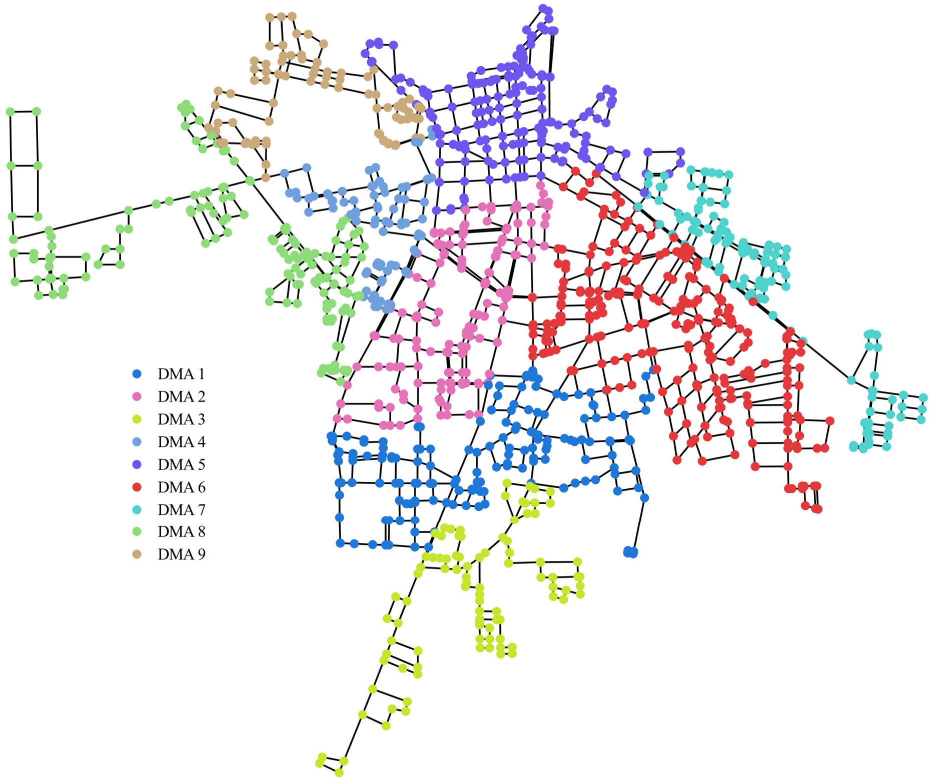

Fig. 3. Matamoros Water Network Partitionig in 9 DMAs

## 4. Conclusions

The proposed procedure provides a simple decision support system for water utilities to choose the optimal partitioning of their water supply networks by employing SWANP 2.0 software and a novel multi objective function that integrates hydraulic performance and investment cost. The simulation results for the large water network in Mexico showed good results obtained with MOF, even with a space solution of k=15 DMAs, so large that it required a heuristic optimization procedure based on a genetic algorithm. Once the maximum number of DMAs, the maximum resilience deviation, and the corresponding budget are defined the procedure provides a user friendly DSS diagram to choose the optimal layout of water network partitioning, in terms of cost and performance.

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