Battle of the Water Networks District Metered Areas

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Abstract: The Battle of Water Networks District Metered Areas (BWNDMA) was the latest of the Battle of Water Networks competition series held at the 18th Water Distribution Systems Analysis Conference (WDSA 2016) as part of ASCE's Environmental and Water Resources Institute (EWRI) stand-alone conferences in Cartagena, Colombia in July 2016. In these competitions, the main objective was to address a specific problem related to water distribution systems (WDS) regarding how to optimize the design and operation of the system's main components. This time, the competition was focused on the challenge of WDS network sectorization, that is, determination of the new district metered areas (DMAs) for an existing network. Design requirements involved constraints related to costs, pressure uniformity, and water quality. Changes in valve and pump operations were needed to supply demands at adequate pressures and acceptable water quality for the given supply scenarios: a wet season and a dry season with water shortages. Seven teams from different parts of the world participated in the BWNDMA and presented their solutions at a special session during the 18th WDSA. This article summarizes the BWNDMA teams' approaches, outcomes, and learned lessons for solving the challenging stated problem. An analysis of some of the decisions that were taken is presented; for instance, some teams ignored the demand similarity criterion, the water age criterion, the pressure restrictions, or the constraints in the water rate that could be extracted from sources. The approaches developed in the BWNDMA represent the state-of-the-art with respect to the analysis of hydraulic conditions in DMAs of real-world water distribution networks for which it is mandatory to make efficient use of available water resources. **DOI: 10.1061/(ASCE)WR.1943-5452.0001035.** *© 2019 American Society of Civil Engineers.*

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Introduction

The Battle of Water Networks District Metered Areas (BWNDMA) was the sixth battle competition held as part of the Water Distribution Systems Analysis Conference (WDSA) series. The competition dates back to 1985, with the Battle of Networks Models (BNM) (Walski et al. 1987) held at Buffalo, NY, as a part of the Computers in Water Resources Conference of the American Society of Civil Engineers (ASCE). Subsequent battles included the Battle of Water Sensor Networks (BWSN) for the 8th WDSA Conference in Cincinnati, Ohio (Ostfeld et al. 2008), the Battle of the Calibration Networks (BWCN) held at the 12th WDSA Conference in Tucson, Arizona (Ostfeld et al. 2012), the Second Battle of Water Networks Design (BWN-II) in the 14th WDSA Conference in Adelaide, Australia (Marchi et al. 2014), and the more recent Battle of Background Leakage Assessment for Water Networks (BBLAWN) held at the 16th WDSA Conference in Bari, Italy (Giustolisi et al. 2016).

Since the beginning of this battle competition, the goal was to attract groups or individuals from academia, consulting firms, and water utilities to submit strategies and proposals for addressing complex problems in real water distribution systems (WDS). In the first battle competition, the original BNM sought to bring together researchers and engineers to propose solutions for the WDS design (Walski et al. 1987). For this first edition of the competition, the proposed network had features and problems that may be found in a real network. To solve the problem, traditional and well-known methods and strategies were applied by each team (Walski et al. 1987). Therefore, each group applied its own research to the same problem, which started to be known as a way of benchmarking new methods.

The BWNDMA at the WDSA 2016 Conference invited groups and participants to propose a solution for the operation of the E-Town network, providing a complex benchmark network to test state-of-the-art methods, similarly to the first BNM. The results of the participant teams for the BWNDMA were presented at a special session during the 18th WDSA Conference in Cartagena, Colombia, in July 2016. The BWNDMA's goal was to attract groups with different backgrounds to propose a method for solving a challenging problem regarding a WDS under several restraints and conditions. The objective of this paper is to present the BWNDMA problem, define

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the rules and the assessment method for the competition, and conclude with a comparison of the results submitted by the participant teams.

Background

The concept of DMA management was introduced in the 1990s by the United Kingdom water industry; at first, DMAs were defined as discrete areas of a distribution system usually created by the closure of valves or the complete disconnection of pipes, in which the quantities of water entering and leaving the area are metered (Water Loss Task Force 2007). The United Kingdom's water industry argued that the use of DMAs should not be regarded as a quick fix but as a long-term commitment between decision makers and water utilities. The introduction of the DMA concept in WDS was first proposed as a tool for reducing leakage in the system. However, definition of boundaries for a DMA sectorization is a complex task because it has to consider economic as well as hydraulic aspects of WDS, such as the high number of variables and constraints in the system (Savic and Ferrari 2014).

Currently, an opportunity exists to change the traditional management approach of WDS from passive to proactive. For instance, most water utilities have only a reactive leakage management protocol, repairing broken or burst water mains and leaks that have been reported by customers or that have become visible on the surface. Nonetheless, researchers have found that unreported leaks, which are not visible to the water supplier or to customers, may account for larger amounts of lost water (Thornton et al. 2008) given that these leaks run constantly for long periods until the water supplier identifies the leakage and reacts to it. For this reason, researchers identified the feasibility of considering proactive and smart approaches based on current monitoring and control technologies, together with the introduction of DMAs. The partitioning of WDS may be permanent or temporary; permanent districts defined are called a DMA partitioning. This partition may be done through the insertion of boundary valves and flow meters at the entrance of each subsystem; these boundary or gate valves can be closed permanently or controlled remotely (Di Nardo et al. 2014).

Traditional approaches in urban WDS are based on looped systems in which multiple flow paths connect each demand node in a city. Looped systems provide redundancy and thereby prevent stagnation and accomplish relatively uniform water pressure and high network resilience—considered important elements of a reliable supply service (Ferrari et al. 2014). However, good reasons exist to believe that it may be convenient to divide the network into independent DMAs.

Researchers agree that the partitioning of a network with DMAs may represent challenges in water distribution; however, most of them consider that the benefits of DMAs are greater than the drawbacks. The main benefits of DMAs are (1) better pressure control management techniques; (2) easier identification and reduction of water losses and leakage; (3) better control of flows to improve water balance; and (4) more efficient control of the spread of dangerous contaminants and pollutants, which may protect customers from attacks (Scarpa et al. 2016; Di Nardo et al. 2014). In contrast, the main drawback of DMAs is that network resilience may be lower than in the original network because fewer flow paths are available to connect supply sources and demand nodes. This decreased resilience may have a negative impact in emergencies, for example, fire flows, pipe bursts, control system failures, and pump station failures (Scarpa et al. 2016).

Nevertheless, despite the drawbacks previously mentioned, in some cases, DMA partitioning may have a positive impact on the system. For instance, when a city has several water supply sources, each with its own water quality, it may be difficult to predict and control this parameter within the network—a common scenario in developing countries. In this case, the benefits of a resilient network are less important than the benefits of controlling the water sources that provide water to each DMA (Di Nardo et al. 2014). In addition to water quality issues, there are several cases in which the existence of multiple interconnected water supply sources may represent considerable losses by unaccounted-for-water, which is the case for some cities in Mexico (Tzatchkov et al. 2006).

Furthermore, because every district is completely isolated, DMAs may reduce the risk of accidental or malicious contamination of the entire WDS, which provides effective protection of the system (Di Nardo et al. 2014). Isolating districts is also useful when maintenance and burst repairs are scheduled because it allows utilities to disconnect only those parts of the network that have been affected. Sectorization is useful to monitor leakage in each district and can be undertaken by analyzing the minimum night flow due to the full isolation and the measurement of flows in several key control points of the network. Because of permanent pressure control, it is possible to maintain low leakage levels in the WDS (Ferrari et al. 2014). Smaller DMAs would make it easier to identify small leakages but are inconvenient and more expensive because they require more pipe closures and the installation of more valves between DMAs (Scarpa et al. 2016). Thus, an optimal number of DMAs must be determined to make good use of leakage detection teams and equipment.

Finally, worth noting is that redesigning a WDS to include DMAs is not a trivial issue. If this task is not performed carefully, it may lead to supply problems, reduced reliability, and decreased water quality (Ferrari et al. 2014). Important aspects exist to verifying each proposed DMA partitioning and, thus, ensure that the network behaves properly in emergencies. The most important aspects are fire flow emergency response and water quality controls. One way to control the latter is to consider the water age in the network (Scarpa et al. 2016). Water quality is an important factor given the differences between looped networks and partitioned networks because it is possible that several dead ends are created in the latter, which may have a negative impact on water age in the network.

For these reasons, it is important to compare the performance between the original looped WDS and its corresponding partitioned version. Murray et al. (2010) showed that it is possible to define DMAs in a WDS without compromising either reliability in water supply or water quality in the system. Network performance was found to decrease when connections between DMAs cannot be avoided and water can flow to a downstream DMA. Thus, it is important to use independent DMAs (Murray et al. 2010). In addition, because isolated DMAs are supplied directly by the transmission main, a WDS is therefore more reliable, water quality is better, and the possible spread of contaminants is reduced (Murray et al. 2010).

Grayman et al. (2009) found that, in large systems, there are no significant differences in water quality that is calculated as the water age of the network. When comparing a looped network with its sectorized counterpart, there can be significant variations in water age in nodes. However, when the entire network is considered, variations were not significant. Comparing fire flows, the authors found that a variation of about 18% existed in the number of nodes with acceptable pressures to comply with fire flows in large networks. However, sectorization was found to significantly improve water security related metrics, reducing the number of people and pipes exposed to contamination incidents by 60%–85% (Grayman et al. 2009). For these reasons, it is possible to conclude that the drawbacks of sectorization are less significant than the benefits obtained in the tested metrics, at least in large systems.

Problem Description

The municipality of E-Town, an important city in Colombia, sought to change its current infrastructure given problems related to water distribution. This town had promising growth opportunities from its tourist potential and Colombia's overall economic growth. However, E-Town was experiencing some issues with the operative configuration of its WDS, mainly from scarce water sources.

The city's water utility was interested in modifying the current DMA configuration to make efficient use of available water and to propose several infrastructure changes for 2022. A calibrated hydraulic model of the current network that included some of the proposed interventions in the future was used to solve the BWNDMA problem. The network model included forecasted demands, demand patterns, existing pump and tank characteristics, and current valve controls (i.e., participant teams did not need to assess population growth nor changes in demand because they were already included in the .inp file). The model showed that the existing DMA configuration was not able to deliver water efficiently because considerable differences existed in the pressure conditions in the city and because some tanks were not being used.

The main goal in this problem was to propose a new DMA configuration to allow the water utility to function, for instance, with the minimal number of DMAs possible, each one with a similar total demand. Other objectives were to guarantee pressure uniformity across the municipality, meet water quality goals, and ensure efficient system operation for a variety of weather conditions throughout the year.

Three water treatment plants (WTPs) supply E-Town's WDS: Bachue, Cuza, and Bochica. During the wet seasons (March, April, May, September, October, and November), these WTP can supply all of the water demanded by E-Town; however, during the dry seasons (December, January, February, June, July, and August), the water utility is forced to use an aquifer to meet demand. This water is redirected to two pump stations: Mohan and Fagua.

For the competition, the proposed DMA configuration must be designed for the wet season, which was the most common weather pattern in E-Town. Nevertheless, participant proposals needed to provide a list of the operational changes that should be implemented in the system for the dry season to fulfill its hydraulic requirements. In 2014, the E-Town WDS had defined some DMAs. By that year, the city was supplied by several pump stations that took water from an aquifer, and Poporo WTP provided 40% of the water from surface sources. However, with this supply configuration, the city had serious problems ensuring reliable water delivery. The supply configuration that will operate from 2022 eliminated the Poporo WTP (which started working only as a storage tank) because a substantial portion of new developments in the city have been built at higher elevations than in the old city. Thus, Poporo WTP can no longer service them.

E-Town Network Description

The E-Town network is large and complex; it consists of 11,063 nodes, five reservoirs (constant head), 17 water tanks (variable head), 13,896 pipes, three pumps, and 14 valves organized in an initial configuration of 15 DMAs that need to be updated, as is shown in Fig. 1. The range of demand and nondemand node elevations in the system is between 0 and 198.5 m above sea level. However, approximately 70% of the nodes in the network have an elevation lower than 25.2 m. For that reason, it is possible to conclude that E-Town is mostly a flat coastal system. The system was simulated for a total extended period duration of 168 h. This network was modified to preserve the anonymity of the real network on which E-Town is based. All data for existing network components were available in the EPANET version 2.00.12 (USEPA 2002) input file *ETown.inp*, which was provided as supplemental material to the participant teams.

For the BWNDMA, several simplifications were made to avoid the inclusion of more variables in the problem. For instance, it was stated that the interest rate does not change over time to simplify this problem (i.e., the capital costs were annualized considering a 0% discount rate). Thus, for the evaluation of the submitted solutions, only one year was considered. However, it is important to clarify that a real-world design problem must consider both the interest rate and the design life of the project to perform a capital costs assessment because most of the time water works are funded with bonds or state-emitted debt (Davis 2010). Considering these simplifications, the new pipe diameters available for the network redesign are given in Table 1. This table shows annual costs for new pipes, annual costs for new parallel pipes (these have a 20% additional cost), and annual valve costs for a range of available pipe diameters. These annual costs are used to calculate the capital costs for that proposed solution. It was stated that for E-Town, replacing pipes with a diameter smaller than 152 mm to reduce disturbances to the city's operations was not cost-efficient. The absolute roughness ($k_s \quad or \quad \varepsilon$) for all of the diameters was 0.01 mm and the minor loss coefficient per length unit was set to 0.02 per meter.

The installation of pressure reducing valves (PRVs) is allowed to achieve the desired DMA configuration. The pressure settings on controlled nodes could not vary over time. Therefore, the settings could only be changed between seasons (wet and dry). The main objective of installing PRVs in the system was to define different DMAs. For this reason, a maximum of two PRVs installed at the entrance of each DMA was allowed. E-Town's water utility had already installed flow control valves (FCVs), and the status and settings of these elements could be changed at no additional cost. However, the valve settings could only be modified between wet and dry seasons. Thus, the status and settings of the FCVs could not be changed during the simulation.

Because of the increased demands, more storage capacity in the system could be added, but only by adding more capacity in the existing tank locations given land property rights. The new tanks were assumed to have the same height and bottom elevation as adjacent existing tanks; thus, there was no need to install new valves to control the system. New tanks had standard prespecified sizes as presented in Table 2, along with their annual maintenance costs. These costs include the connection of the new tank to the network. E-Town's WDS had several tanks that were out of service (control valves to the tanks in the hydraulic model were closed). Battle competitors were allowed to use these tanks by installing FCVs at the tanks at no additional cost.

E-Town's WDS was supplied mainly by surface sources, except during the dry season, when it was necessary to pump water from the city's aquifer. The three pump stations included in the original model corresponded to the two wells from which water was obtained (Mohan pump station has two pumps). These pump stations could operate all day during the dry season, and adding hydraulic controls in the model was permitted. Using time-controlled pumps or variable speed pumps or modifying the pump curves was not possible. It is important to clarify that, for the BWNDMA, energy costs were not considered. However, a real-world design problem must consider energy costs because they might be one of the largest costs in the system.

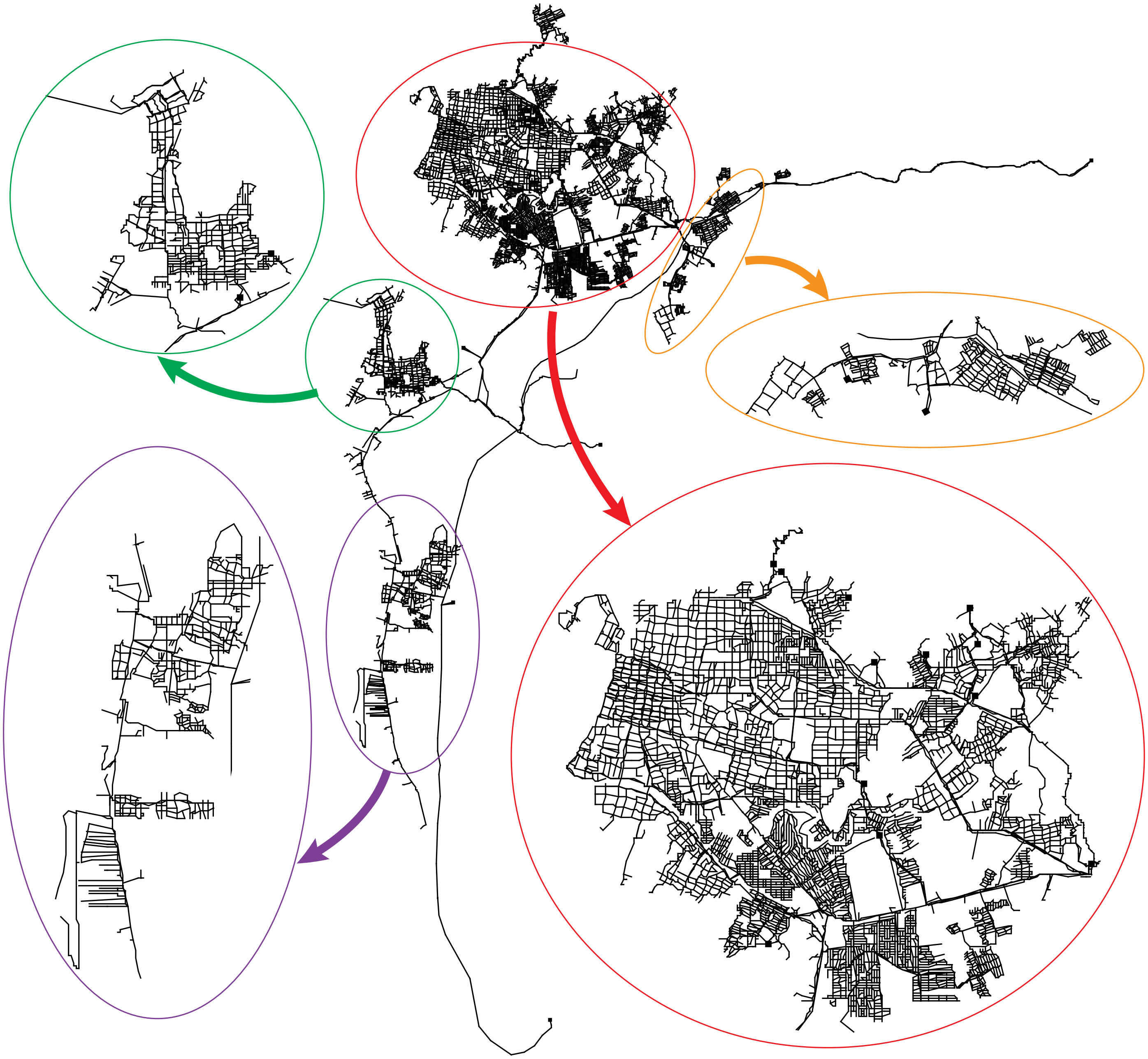

Fig. 1. E-Town water distribution system layout.

Table 1. Pipes and PRVs annual costs

Diameter (mm)	New pipe costs ($/m)	Parallel pipe costs ($/m)	PRVs installation costs ($)
102	—	—	315
152	—	—	695
203	23.31	27.97	1,501
254	26.09	31.3	2,240
305	29.86	35.83	3,711
356	32.56	39.07	4,470
406	35.35	42.42	7,400
457	38.56	46.27	7,733
508	41.87	50.25	7,750
610	62.18	74.62	9,211
711	69.96	83.95	10,685
762	73.46	88.15	11,708

Table 2. Tanks annual costs

Volume (m^3)	Annual cost ($/year)
500	38,827
1,000	53,387
2,000	63,093
3,750	100,258

Supply Scenarios

As was stated previously, E-Town had two different supply scenarios: wet season and dry season. Addressing the problem was required for the wet season, which was the predominant one; however, the system had to perform for the dry season scenario as well, with both being assessed using the same criteria.

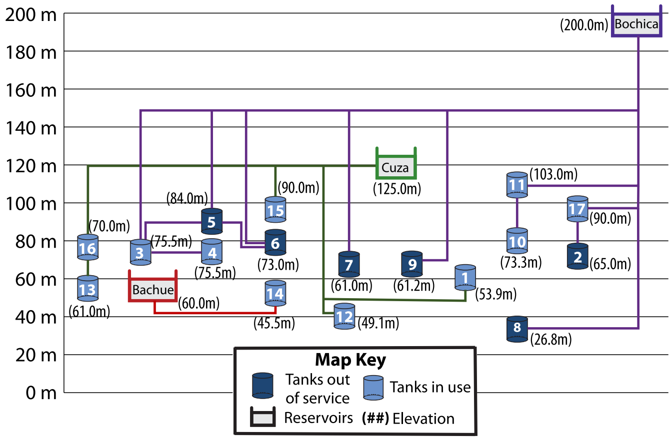

Fig. 2. Supply configuration during wet season.

For the wet season, the water utility required that every demand node of the network had water delivered to it at a proper pressure. Nodes without demand were only required to maintain pressure higher than zero. Only three nodes could violate this restriction because they were located upstream of the pump stations. The minimum pressure for demand nodes was 15 m. An additional requirement was that, at the end of the extended period simulation (168 h), each tank must have at least the same volume of water that it had at the beginning of the simulation (60% of its total capacity). During the simulation, the level of each tank must lie between 10% and 90% of its total capacity. Fig. 2 presents the desired supply configuration regarding the main pipe system of E-Town during the wet season.

In contrast, the dry season presented a challenge in terms of providing a reliable supply to meet E-Town's demand. The water utility's main concern about failing to provide adequate supply was exclusively given forced changes in the supply system during the dry season. This concern occurred because, during these times of the year, the maximum flow available from the WTPs decreased considerably, and the city had to use two pump stations that drew water from underground sources. Table 3 presents the maximum flow rates that could be extracted from each water source during both wet and dry seasons. Changes in the supply system led to inadequate network operation because of zones of high and low pressures, unexpected flow directions, and tank emptying. In this sense, the water utility desired a DMA configuration that could accomplish all of the requirements previously described during both the wet and dry seasons with minimum changes in the network.

In the EPANET model, three FCVs were installed with maximum flows during the dry season for each WTP. Additionally, the settings in Bochica's WTP FCVs could be modified, but the sum of these two flow rates must be a maximum of 420 L/s, which is the maximum flow rate that could be extracted from this groundwater source during the dry season.

Table 3. HGL and maximum flow rate per water source and season of the year

Water source	Flow in wet season (L/s)	Flow in dry season (L/s)	Hydraulic grade line (m)
Bachue WTP	450	240	60
Bochica WTP	800	420	200
Cuza WTP	1,600	900	125
Mohan pump station	NR	206	0
Fagua pump station	NR	314	0

Note: NR = not required.

Assessment Criteria

The proposed solutions submitted for the BWNDMA was expected to comply with the minimum requirements and performance criteria described in this section. To summarize, requirements existed for the number of DMAs, total costs, pressure uniformity, water quality, and the number of valves setting changes.

DMA Configuration

A DMA was considered an isolated area with the pressure at one or at most two entrances (in normal operation conditions) regulated by one or two pressure reduction valves (PRV). Because a PRV simulates a flow measurement device, it is installed at the entrance of each DMA. In the EPANET model, the status of the PRV may be set as *OPEN* to simulate a valve that does not have a regulation function in the system.

The water utility considered 15 DMAs manageable and convenient; therefore, solutions that approach this number from the top were favored. The minimum number of DMAs must be 15, and this requirement was assessed through the following equation:

$$DMA_{\text{index}} = N_{DMA} - 15 \tag{1}$$

where DMA_{index} = index that evaluated the performance of each solution and N_{DMA} = the number of DMAs that were defined for the specific solution. In addition, for operational reasons, each DMA should have a similar demand (i.e., a similar number of users). Eq. 2 was used to assess this similarity

$$DS = \sqrt{\frac{1}{N_{DMA}} \cdot \sum_{i=1}^{N_{DMA}} (V_{in,i} - V_{out,i} - V_{avg})^2} \tag{2}$$

where DS = demand similarity index (in m^3) and N_{DMA} = proposed number of DMAs in the solution. $V_{in,i}$ = volume of water (in m^3) that flows into the DMA during the week and is calculated as follows:

$$V_{in,i} = \sum_{j=1}^{M} (Q_{D,j} \cdot \Delta t) \tag{3}$$

where $Q_{D,j}$ = flow that enters during period j (in weeks) as the time index $(j = 1, 2, \ldots, M)$; Δt = period of hydraulic modelling (1 h); and M = total number of simulation time steps. $V_{out,i}$ = output volume during the simulation week that goes to another DMA (in the case in which one DMA supplied water to a downstream DMA) and is estimated as follows:

$$V_{out,j} = \sum_{j=1}^{M} (Q_{D,j} \cdot \Delta t) \tag{4}$$

where $Q_{D,j}$ = demand during period j (in weeks) as the time index $(j = 1, 2, \ldots, M)$ and Δt = period of hydraulic modeling (1 h). V_{avg} = average volume of net inflow across the DMAs, defined as follows:

$$V_{avg} = \frac{\sum_{i=1}^{N_{DMA}} (V_{in,i} - V_{out,i})}{N_{DMA}} \tag{5}$$

The previous equations were applied for solutions that had 15 or more DMAs; thus, a solution with fewer than 14 DMAs was not accepted. It was desirable that all demand nodes were included in a DMA. However, given its physical isolation in the system, a maximum of 55 nodes could be outside a DMA. Nondemand nodes could also be outside DMAs.

Costs

The water utility desired a low-cost solution, that is, material costs for pipes, tanks, valves, and construction. The following equation was used to assess the capital cost of a proposed solution:

$$CC_{net} = \sum_{i=1}^{N} C_i L_i + \sum_{j=1}^{M} K_j + \sum_{z=1}^{P} V_z \tag{6}$$

where CC_{net} = network capital costs investment; C_i = cost of the ith pipe according to its diameter; L_i = length of the ith pipe in mm; i = new pipes index (N is the total number of changed pipes); K_j = cost of the jth valve according to its diameter; j = new valves index (M is the total number of installed valves); V_z = cost of the zth tank according to its volume; and z = new tanks index (P is the total number of installed tanks).

Pressure Uniformity

To maintain a similar level of water supply service to all customers, to facilitate the operation of the WDS, and to guarantee that energy was properly used in the system, the water utility sought to accomplish pressure uniformity throughout the network. Uniformity was analyzed from two perspectives: (1) all consumption nodes must have water delivered with a minimum pressure of 15 m for the peak demand, and (2) all nodes in the network should have a similar pressure that should be as close as possible to the minimum pressure. The pressure uniformity in the network was defined using an expression based on an equation proposed by Alhimiary and Alsuhaily (2007)

$$PU_{net} = \sum_{j=1}^{M} \left[\frac{1}{N} \sum_{i=1}^{N} \left(\frac{P_{i,j} - P_{min}}{P_{min}} \right) + \frac{\sqrt{\frac{\sum_{i=1}^{N} (P_{i,j} - P_{avg,j})^2}{N}}}{P_{avg,j}} \right] \tag{7}$$

where PU_{net} = pressure uniformity (nondimensional); $P_{i,j}$ = pressure at junction i at time t_j (in m); P_{min} = required minimum pressure of 15 m; i = junction index $(i = 1, 2, \ldots, N)$; j = time index $(j = 1, 2, \ldots, M)$; t_j = simulation time; $t_j = j\Delta t$ is the time step (equal to 1 h); and $P_{avg,j}$ = average pressure in the network at time j, defined as follows:

$$P_{avg,j} = \frac{\sum_{i=1}^{N} P_{i,j}}{N} \tag{8}$$

The pressure uniformity was assessed only for demand nodes. As an additional condition, whereas there were no restrictions in the maximum pressure in the main pipe system of the municipality, no DMA pipe could have a pressure higher than 60 m at any time of the week. This restriction is valid only for pipes within a DMA.

Water Quality

Water quality was assessed by the water utility through the computation of water age in the network nodes. Currently, the preferred water age is exceeded in some parts of the network; thus, for the future, the water age should be reduced. The water utility has defined the network water age as it was implemented previously for the BWN-II (Marchi et al. 2014)

$$WA_{net} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} k_i^{(j)} Q_{D,i}^{(j)} \cdot (WA_i^{(j)} - WA_{\lim})}{\sum_{i=1}^{N} \sum_{j=1}^{M} Q_{D,i}^{(j)}} \tag{9}$$

where WA_{net} = network's weighted average water age above the limit (in hours); $WA_{i,j}$ = water age at junction i at time t_j (excluding tanks and reservoirs); $Q_{D,i}^{(j)}$ = demand (in m^3) at junction i and time t_j; i = junction index $(i = 1, 2, \ldots, N)$ and j = time index $(j = 1, 2, \ldots, M)$; t_j = simulation time; and $t_j = j\Delta t$ is the time step, which equals to 1 min. WA_{lim} = limit of water age (in hours) allowed by Colombian regulation (60 h) and $k_i^{(j)}$ is a binary variable defined as 1 if the water age exceeds the limit or 0 if it does not, as follows:

$$k_i^{(j)} = \begin{cases} 1, & WA_i^{(j)} \geq WA_{lim} \\ 0, & WA_i^{(j)} < WA_{lim} \end{cases} \tag{10}$$

Therefore, that the water age is only considered at nonzero demand nodes and gives greater importance to nodes with larger water demands. It also only considers water age at junctions (excluding tanks and water sources). Finally, the threshold for the water age was defined according to the existing regulation in Colombia.

Operational Changes

Changes correspond to the opening and closure of isolation valves [represented in EPANET (USEPA 2002) with the opening or closure of pipes] and the operation of PRVs and FCVs. The number of changes necessary for the dry season were assessed through the following equation:

$$OpCH_{net} = \sum_{i=1}^{N} k_i + \sum_{j=1}^{M} b_j \tag{11}$$

where $OpCH_{net}$ = operational changes index of the network; k_i is a variable that equals 1 if the ith pipe was closed during the dry season and 0 if that pipe was not modified; i = pipe index (i = 1, 2, $\ldots$, N); b_j is a variable that equals 1 if the jth PRV (or FCV) setting was modified during the dry season and 0 if that PRV (or FCV) setting was not modified; and j = valve index $(j = 1, 2, \ldots, M)$.

Assessment of Participant Solutions

Each team was required to submit only one solution regardless of the optimization method used. Submitted solutions were assessed considering the eight criteria previously described and two additional criteria: the committee score and the survey results obtained during the special session at the conference. The final score for each team was calculated considering the range among all participants for each criterion, which indicates that the score was normalized using all of the solutions with the following equation:

$$FS_j = \sum_{i=1}^{8} \frac{(S_{i,max} - S_{i,j})}{(S_{i,max} - S_{i,min})} + \sum_{i=9}^{10} \frac{\left(\frac{1}{S_{i,max}} - \frac{1}{S_{i,j}}\right)}{\left(\frac{1}{S_{i,max}} - \frac{1}{S_{i,min}}\right)} \tag{12}$$

where FS_j = final score of team j; $S_{i,max}$ = maximum score in each criterion accomplished by the worst team; $S_{i,j}$ = score of the jth team for the ith criterion; and $S_{i,min}$ = minimum score in each criterion accomplished by the best team. The solutions were ranked using the FS_j scores, and the team with the highest overall rank was selected as the winner of BWNDMA.

Table 4. Summary of methods and simplifications proposed by BWNDMA participant teams

Team	Simplifications in criteria	Computational strategy	Optimization algorithm
1	Reduced the number of objectives, taking water age as a constraint.	Did not considered water age in each iteration because it was almost zero.	ASO
2	Ignored demand similarity and favored a small number of DMAs (smaller costs and better water age).	N/A	Trial and error based on engineering judgment.
3	Ignored the number of DMAs and instead worked with uniformity of DMAs.	Skeletonization provides maximum simplification to reduce computational times.	METIS algorithm and PGA.
4	N/A	Optimized for a steady-state simulation (minimum and maximum demands).	PSO, GA, and SLC.
5	Ignored the restriction of the maximum water flow rate that may be obtained from one of the WTP.	Used a software different from EPANET to run hydraulic solver.	BFS, Darwin optimization framework, and shortest path algorithm.
6	Performed multiobjective optimization considering all objective functions (minimize cost, water age and pressure uniformity).	N/A	MOGA and NSGA-II.
7	Discarded the total cost criterion, focusing on the other constraints.	Modified the original .inp file until hydraulic conditions were set properly to reduce run time.	Defined DMAs graphically in ArcMap version 10.3.1 and iterated until pressure constraints were met.

Note: ASO = agent swarm optimization; PGA = pseudogenetic algorithm; PSO = particle swarm optimization; GA = genetic algorithms; SLC = soccer league competition; BFS = breadth-first search; MOGA = multiobjective evolutionary algorithm; and NSGA-II = nonsorting genetic algorithm.

Competitor Solution Methods

Contributions made by each group are now presented by describing the different methods proposed to address the problem stated for the BWNDMA. In Table 4, a summary of different features related to the solutions is presented.

Gilbert et al. (2017) employed engineering judgment, network graph simplification, and visualization tools in a multistage process to find a feasible initial solution. Porteau Software was used to identify isolated parts of the network such that data errors and isolated nodes without a water source could be fixed. The initial DMA boundaries were further optimized using agent swarm optimization (ASO) to achieve feasible solutions with better costs of implementation, demand similarity among DMAs, and better operational objectives. Finally, tailored and scalable sequential convex optimization tools optimized the operational settings of valves and pumps.

Salomons et al. (2017) proposed a method based on engineering judgment, developed as a multistage design approach. First, source allocation and general design were developed for the operational zones. Subsequently, tank volumes were adjusted to meet their constraints, and DMAs were introduced to satisfy pressure regulations. Finally, a detailed design and a fine-tuning of the operations were carried out. An interesting element of this method is the source allocation process through which natural offer/supply zones are identified and used when designing the network for each of these zones. This process guarantees that water from the sources flows through the tanks.

Martínez-Solano et al. (2018) proposed a solution method that merged engineering judgment and heuristics. In this approximation, three simplified scenarios were considered: maximum demand, minimum demand, and average demand, which represent maximum pressure, minimum pressure, and tank-level behavior. The DMA configuration was performed using engineering judgment, and the METIS algorithm (Karypis and Kumar 1998b) and pseudogenetic algorithm (PGA) were subsequently used to generate graphs to find an optimal configuration for pipe closures.

Brentan et al. (2018) also proposed a method that involved engineering judgment and a set of different heuristics. Graph clustering and social network theory were used to define the DMAs limits. Subsequently, pipe diameters and valves configuration were optimized using three heuristics: particle swarm optimization (PSO), genetic algorithms (GA), and soccer league competition (SLC).

Rahman and Wu (2018) proposed a method that merged engineering judgments with simulation-optimization methods. First, the main pipe network and the source nodes by pipe diameters were identified. These source nodes became candidates for DMAs' entry points and were subsequently defined using the breadth-first search (BFS) method. Then, the Darwin optimization framework and the shortest path algorithm were used for the optimization of DMA partitions to identify entry points among the source nodes with a minimized demand dissimilarity. The DMAs boundaries were fine-tuned by limiting the number of inlets to two pipes, and pressure requirements were met by excluding high elevation nodes. Finally, the system's interventions were optimized to address the criteria, for example, pressure uniformity and water age, among others, throughout the system.

Rahmani et al. (2018) proposed a method based on graph theory and optimization approaches. The method consisted of three sequential phases: (1) preliminary analysis, (2) DMA configuration using graph theory and adjustment based on demand similarities, and (3) optimal operation of the system using a number of consecutive single and multi-objective optimization problem settings. The objectives included minimizing total cost, water age, and pressure uniformity indicators for wet as well as dry seasons.

The last group (Pesantez et al., unpublished data) proposed a method based on the topological analysis of the network as well as engineering judgment. First, a preliminary analysis of the system's components was performed using a graphical method. This analysis was carried out such that the main pipe network, the closure of valves, the tanks control configuration, and DMA limits could be determined. Subsequently, a semi-automatic analysis was performed using geospatial analysis to graphically redefine the DMAs proposed during the first stage. Finally, the EPANET toolkit was used to verify that all restrictions were being taken into account.

Results

As previously mentioned, all solutions submitted were required to comply with a series of different criteria. Each group was asked to submit only one solution for the wet season and specify the operational changes to implement to address the dry season. Therefore, for the evaluation process, the BWNDMA committee established problem restrictions based on the minimum requirements and used

Table 5. Performance criteria values of the submitted solutions as recomputed by the BWNDMA committee

					Wet season		Dry season	
Team	DMA_{index}	Demand similarity	Total costs ($)	Operational changes	Pressure uniformity	Water age (h)	Pressure uniformity	Water age (h)
Gilbert et al.	16	3.51×10^7	**$332,024.40**	14	324.23	0.0047	323.00	**0.0050**
Salomons et al.	8	1.05×10^8	$613,244.36	**5**	308.03	0.0049	310.00	0.0065
Martínez-Solano et al.	44	3.39×10^7	$653,941.64	**5**	**262.38**	0.0045	**261.92**	0.0054
Brentan et al.	**0**	1.16×10^8	$12,972,011.0	208	395.84	0.3200	N/A[a]	0.7180
Rahman et al.	1	4.88×10^7	$713,772.40	17	323.32	**0.0045**	326.98	0.0690
Rahmani et al.	**0**	$\mathbf{2.68} \times 10^7$	$1,641,520.00	31	428.46	0.0398	330.17	0.0246
Pesantez et al.	3	5.67×10^7	$440,721.12	15	368.04	0.0052	N/A[a]	1.8430
Minimum	0	2.68×10^7	$332,024.40	5	262.38	0.0045	261.92	0.0050
Average	10.3	6.02×10^7	$2,481,033.56	42.1	344.33	0.0550	310.41	0.3800
Maximum	44	1.16×10^7	$12,972,011.0	208	428.46	0.3200	330.16	1.8400

Note: In all criteria, lower values were preferred. Values given in bold are the best values for that criterion.

[a] It was not possible to calculate and check the obtained results for these groups by the BWNDMA committee.

the performance criteria to evaluate the performance of each solution. The purpose of this section is to present the results to the problem submitted by the participants. However, to ensure consistency in the results between different groups and a fair ranking, the Committee simulated the submitted solutions and recalculated the results reported by each group. These results are shown in Table 5. Discrepancies in performance criteria values between submitted solutions and those recalculated and validated by the BWNDMA Committee were expected. For this reason, presenting only the results recalculated by the BWNDMA Committee was decided.

Potential discrepancies could have been identified given the method used to calculate energy values (e.g., if the computational time-step used for water quality in EPANET2 is different from the hydraulic solver time-step). Discrepancies may also have occurred from the modification of some of the established parameters in the EPANET2 input file, modifications in the topology of the network, or any other reason that could have affected the calculation and produced misleading results.

Constraints compliance and performance criteria values in the DMA configuration were used for ranking purposes and when selecting the best solution within the conference's special session. The final score of each team solution was obtained using Eq. (12). However, violations of constraints and the final ranking are not presented because the BWNDMA's goal was to attract groups with different backgrounds to propose a method for solving a specific problem regarding a WDS. Researchers had the opportunity to test their own methods and compare it with those from other leading research groups throughout the world. Therefore, ranking the solutions could be unnecessary. It is worth noting that, from a practical point of view, even infeasible solutions may be acceptable because every solution was context- and constraint-dependent.

Analysis of Submitted Methods and Solutions

At first, it must be noted that BWNDMA was complex and is based on a real-world problem. Thus, it was not expected that all participants would be able to apply a full optimization process for all of the performance criteria. Taking this into account, the idea was to compare the decisions that different groups took and analyze the criteria that were the most important for each team. Considering the nature of real WDS design, where even infeasible solutions may become feasible given trade-offs made by the decision maker, the BWNDMA Committee decided to not take into account violations in the restrictions for this paper because they may offer some insights into DMA design methods.

As was stated previously, participant solutions were assessed using Eq. (12), which normalized the score considering all selected criteria. To perform this assessment, a normalized score for every criterion was needed. Normalized scores for every performance criterion for all participant teams are shown in Fig. 3.

Cost is often used as the preferred criterion to compare different solutions. However, because this was a mixed design and operational problem, capital costs were not the only relevant variable in the solution. Thus, costs did not play a significant role in the assessment process. In fact, one participant discarded costs and focused on the other criteria. Nevertheless, general cost performance is presented in Table 5, which indicates that most of the groups had similar values, with solutions less than $1 million.

It is worth noting that the teams with higher costs were those that reached a zero DMA_{index}; therefore, lower costs were achieved if a higher number of DMAs was defined. However, one participant team found that, if the demand similarity criterion was neglected and a lower number of DMAs was favored, capital costs and water quality (measured as water age) could be improved. Several groups explained the reason for this behavior: because there are fewer DMAs, it is possible to use a smaller number of valves, which should decrease capital costs. Participant teams argued that fewer DMAs indicates that there are more flow paths available and, thus, water age criterion should improve and constraints should be more easily met. Therefore, fewer valves and fewer pipe replacements would be needed, reducing capital costs and demonstrating that a small number of DMAs has a beneficial effect on both capital costs and water age in the network. In addition, one of the participant teams stated that it is not possible to assume that every pipe in the network could be used as an isolation pipe, considering that in several countries most pipes do not have isolations valves. For instance, it is usual that only high diameter WDS pipes have valves installed in developing countries and, thus, small diameter pipes do not have any valve. In contrast, in developed countries, most WDS pipes have isolation valves already installed, which can reduce DMA implementation costs. For this reason, only a few pipes should be considered as candidates for DMA boundaries because, in some countries, a real problem is that capital costs could be higher than the costs considered for this problem.

Regarding demand similarity, it was found that most teams achieved good results for this criterion, even for a different number of DMAs. This behavior is shown in Fig. 4, which compares the results from demand similarities to the number of DMAs proposed by each participant team. This criterion has no clear trend. For instance, it was found that obtaining very different values for the

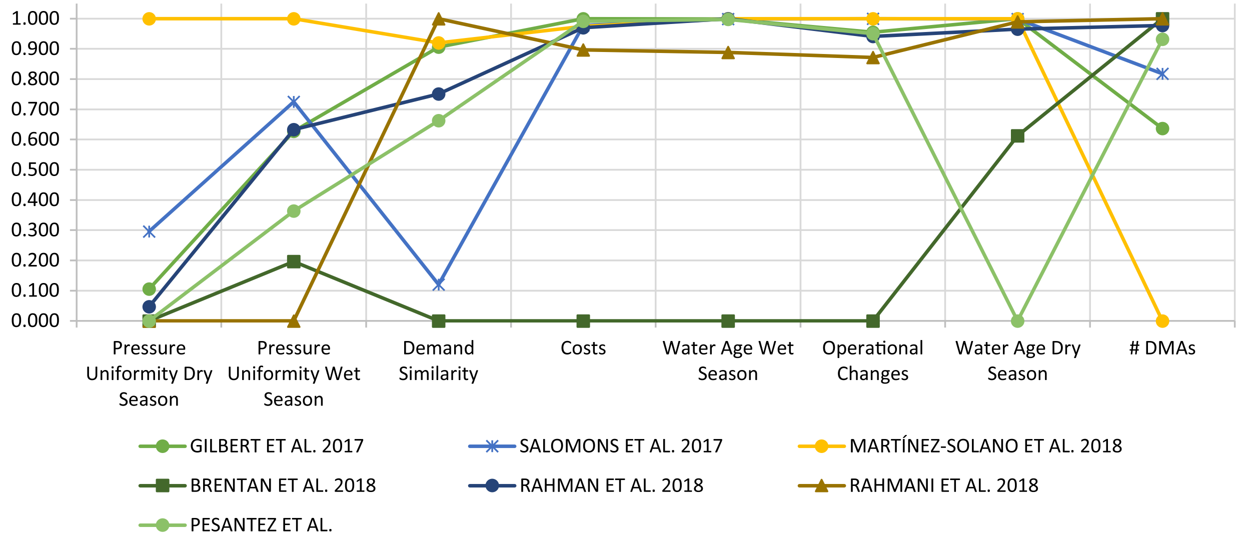

Fig. 3. Normalized scores for every competitor team including all performance criteria.

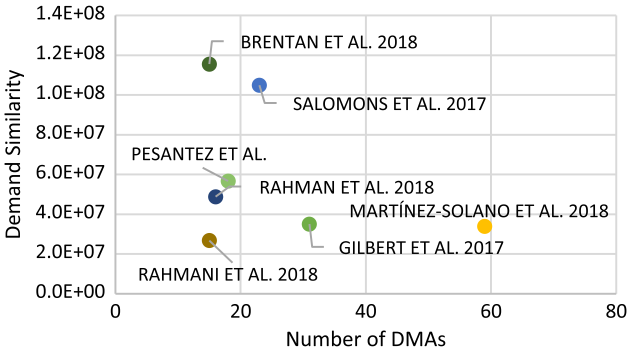

Fig. 4. Comparison of demand similarity and number of DMAs.

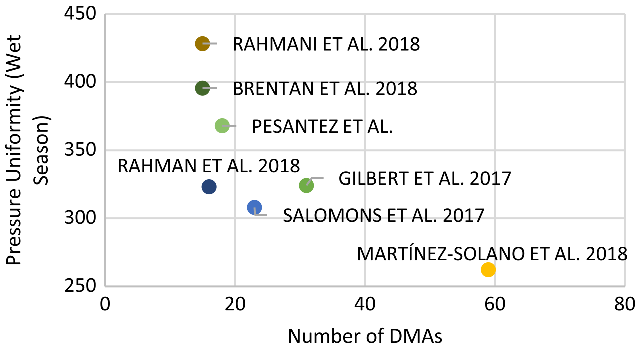

Fig. 5. Comparison of pressure uniformity and number of DMAs.

demand similarity criterion was possible for 15 DMAs. In fact, for solutions with 15 DMAs, the minimum and the maximum demand similarities were obtained. These results were surprising, especially because some participant teams decided to use demand similarity to define DMA size. In fact, some groups even prioritized demand similarity over other criteria, defining the size of DMAs based on its total demand in liters per second or defining that a DMA was too large based on its demand compared with the average demand of the other DMAs.

It is worth noting that most teams considered demand to be an important aspect of its proposed solution. Some teams used demand similarity as a criterion for defining DMAs size, as it was explained, using different methods such as semi-automated or manual resizing of each zone. One of the participant teams found that DMA identification by inspection was not enough to achieve good demand similarity in the network; thus, they preferred automated methods to define DMA partitions to achieve better results in this criterion. It is worth noting that, given the geographical isolation of some nodes, merging some low-demand DMAs was not possible, which affected this criterion.

However, one team decided to ignore the demand similarity criterion, arguing that if they were to achieve a perfect score and follow that criterion, they would have had to define nearly 80 DMAs. For that reason, that team decided to favor fewer DMAs in the network, ignoring demand similarity. Of interest is that the participant team that decided to discard demand similarity was not the team with the highest value in that criterion. In contrast, teams that pursued this criterion got the lowest values in demand similarity, thus supporting a direct correlation between the strategy and the results. For this reason, it was not possible to define a universal rule regarding demand similarity and the number of DMAs in the network. Thus, it is fair to say that a low number of DMAs does not necessarily imply that demand similarity between DMAs is achieved.

Pressure uniformity was the most difficult criterion to fulfill in the problem, as several participant teams reported. The reasons included the network's complex dynamics, such as different entrances and variations in demand and topology. When analyzing the presented results by the participant teams, a clear trend was detected: a lower number of DMAs meant that a wider range of pressure uniformity could be obtained, as presented in Fig. 5. Participant teams' results for pressure uniformity in the wet season had similar values, regardless of costs or demand similarities. It is important to remark that the majority of participant teams first attempted an experience-based DMA distribution considering mainly elevation differences. Several groups stated that this engineering judgment call focused on predefining DMAs following a reasonable criterion: pressure uniformity. Those teams argued that it was not possible to put together nodes with high differences in pressures because that would make it very difficult to comply with maximum and minimum pressure restrictions. For instance, one group stated that it was difficult to comply with the 60-m maximum pressure in nodes with very low elevations. For this reason, the first approach for defining DMAs was to put together nodes with similar elevations.

Another team argued that a small number of DMA partitions in the network negatively affects pressure uniformity because larger DMAs represent worsening of pressure control. The research literature is in accordance with this fact, as it was demonstrated that the purpose of defining DMAs in a network is to have better pressure control thanks to the small-area partitions. For this reason, this group considered pressure as its criterion for defining new DMAs; when pressure constraints were violated, a decision had to be made: to create a new DMA for that zone or to mark that node as a non-DMA node, which was allowed to have pressures higher than 60 m. Therefore, if a new DMA was created, the idea was to connect that DMA directly to the water supply main because it was found that pressure management was easier if DMAs did not interact with each other.

Another approach was to consider that the elevation difference between the nodes connected by a pipe was the perfect value to be defined as the weight for the links in their solution method, which was based on directed graphs. A different team had a very different approach: when it was defining DMAs, if pressure restrictions were violated, those nodes were identified for further revision. Then, using valves, tanks, and pipe replacements, those pressure violations were corrected. Based on the experience of those teams, the importance of pressure differences between nodes to obtain an initial solution to the problem was illustrated. After reviewing participant teams' solutions, the first assumptions were found to be correct: a large number of DMAs positively affects the pressure uniformity criterion. However, it is not true to state that a solution with few DMA partitions must have bad performance in pressure uniformity.

Water quality was not a decisive criterion in the BWNDMA, mainly because water quality measured as water age is not a strong restriction in Colombia. However, it may be remarked that most of the solutions had similar water age values for the wet season, except for one group that had a water age value more than five times higher than the remaining groups (although all solutions fell within a narrow band of water age). One of the groups that defined 15 DMAs in its solution obtained this value. In fact, several groups stated that water age, as a quality criterion in E-Town, was not a hard restriction in the problem. One participant team presented a water balance analysis, which found that stored water in the network was nearly half of the daily demanded volume. Thus, it was reasonable to think that water is replaced twice a day in the network, which is good for water age as quality criterion. For this reason, water age would only represent a problem in isolated dead-ends. Similarly, as was previously presented, one team argued that a small number of DMAs positively affected water age in the network. Moreover, as most of groups had fewer than 25 DMAs as their solution, it would be expected that water age did not represent a challenge.

For those reasons, some participant teams did not consider water age as a restriction in the first stages of their solution methods. For instance, one team considered the problem as a nonlinear complex set of subproblems, but instead neglected the water age criterion because of its near-zero value. Another team ignored water age through the simulation process and at the end made the necessary adjustments following best management practices (BMP). Similarly, some teams performed steady-state simulations for their optimization methods when calculating the water age was not possible. Moreover, at the end, they performed the 168-h extended period simulation to assess water age in the network. Some participant teams reported that only a few demand nodes in the network presented a water age of more than 60 h—more precisely, 0.03% and 6%, as two of the teams reported it. As was expected, the teams that defined more DMAs were those that achieved better water age values for both the wet and the dry seasons.

Finally, most groups did not propose a large number of operational changes to solve the dry season's complications in available water supply sources. Most groups did not propose more than 15 operational changes for this season. However, even when few changes were proposed, participant teams performed poorly with respect to the dry season criteria. For pressure uniformity, some teams were not able to meet the minimum pressure constraint, and for water age, most groups obtained higher values than those obtained for the wet season. Worth noting is that participant teams did not change their defined schemes of DMA partitions to address the dry season problem.

A clear trend was identified: all teams but one solved the problem for the wet season scenario and then proposed operational changes for the dry season scenario; only one team decided to first address the dry season scenario (the more restrictive one) and then check whether any operational change was required for the wet season problem. This group argued that only in the dry season was it difficult to find a feasible solution; thus, if this scenario was solved first, then the wet scenario was also solved. Based on the experience of the other groups, the dry season scenario was the most difficult to solve because of the scarce water supply availability. In fact, two of the participant teams could not find a feasible solution to this problem because their optimization methods could not comply with minimum pressure restrictions or could not handle negative pressures. Another group decided to neglect the restriction on the maximum water that could be extracted from the dry season supply sources, arguing that this scenario requires major engineering interventions that cannot be done considering the restrictions imposed by the BWNDMA problem.

What We Learned about DMA Configuration

The previous section presented some relevant insights obtained from the participant teams in the BWNDMA. The general purpose of this section is to offer some conclusions and general recommendations about sectorization and DMAs, taking into consideration both the research literature and some of the insights. Considering the results obtained by the participant teams, it is relevant to analyze the general performance and reconsider the main benefits and drawbacks of implementing DMAs in a WDS. As was previously stated in the DMA configuration section of this paper, researchers agree that the four main benefits of sectorization are related to pressure management, leakage identification, water balance improvement, and reducing the spread of contaminants in the system (Scarpa et al. 2016).

Pressure and flow control were well discussed indirectly with the statement of the BWNDMA, but the other two of these benefits are also important for the operation of real WDS. For instance, the identification of water losses to reduce leakage in the network depends on how water utilities use available information from flow meters in each DMA and on how water utilities react to pipe bursts and breaks. Similarly, DMAs allow control of the spread of dangerous contaminants through the network only if water utilities have well-defined limits for each DMA, and only if water utilities react properly to emergencies. Those two situations occur during WDS operation and are case-dependent; thus, those situations cannot be analyzed by only considering the proposed DMA definition.

DMA partitioning may be used to achieve better pressure control management and improve flow metering and flow control. As was previously discussed, pressure uniformity can be used to assess how well pressure is managed in the system. Lower pressure uniformity values are desired and, after analyzing results, better pressure uniformity was found to achieve when more DMAs were used, at least for the results presented by the BWNDMA competitors as is shown in Fig. 5. This outcome was expected because it was found that if DMAs are too large, there is less pressure control (i.e., if there are few DMAs). The idea of partitioning the network is to create manageable zones and, as every DMA had one or two inlets, it is possible to control precisely the pressure within each DMA.

Improvements in inflow and outflow control may be partially assessed through the demand similarity criterion because it accounts for inflow and outflow similitude in different DMAs. The BWNDMA results show that demand similarity did not follow any particular trend regarding the number of DMAs and the value of the criterion. For this reason, demand similarity was not relevant if many DMAs were defined to achieve good results in the demand similarity criterion. Hence, it is possible to state that a lower number of DMAs is not necessarily better for achieving good performance in operational objectives. Nevertheless, as was described previously, it was found that most participant teams in the BWNDMA considered demand similarity as an important criterion when deciding whether or not to create a new DMA. In fact, it is important to note that the implementation of fewer DMAs is less expensive but, in contrast, the resulting DMAs will be more dissimilar in pressures and demands between them.

In contrast, researchers argue that the main drawback of DMA partitioning is the reduction in network resilience, regarded as a reduction in supply reliability. As was previously discussed in the background section, a reduction in network resilience may not necessarily be an undesired outcome of DMA implementation because the reduction in pipe loops may be useful for some emergencies (e.g., pipe burst and contaminated water) but not useful for other cases (e.g., fire flow and system failures). In addition, the analysis of submitted solutions found that DMAs performs well for the considered criteria. However, when water sources are changed (i.e., the dry season scenario), the interaction between the main pipelines and the defined DMAs govern the proper response to the modification of water sources. For this reason, it is left as a recommendation for further research on real world networks in relation to supply reliability, including a conscious analysis of network resilience. This analysis should consider all possible scenarios and the fact that there may be benefits and drawbacks in supply reliability with the implementation of DMA partitioning. The evaluation and consideration of resilience in WDN is left for future research work and was not included as an objective to be assessed in the BWNDMA.

Conclusions

It is important to remark that the BWNDMA problem made an important effort to include a real-world problem for which a simplified model based on the distribution network existing in a real city was used. Over time, networks used in battle competitions have been modified to increase their size and complexity to match the increase in computing power and the sophistication of the optimization methods. However, the problems associated with those networks were not based on a real system and included too many simplifications; thus, several situations that may be evident only in real WDS were not taken in account. For this reason, the BWNDMA included a challenging dry season scenario in which water supply sources are scarce.

In addition, the problem was challenging and defied the identification of a global optimal solution given the complexity of a real-sized network, the interactions between different elements, and the decisions required to solve the water supply problem under the proposed restrictions. However, the idea of the BWNDMA was to propose a problem to be solved by different teams and to set some ground rules, but the participants would use their own engineering criteria and know-how to propose a solution for this challenging problem. In fact, none of the participant teams achieved a perfect score for all of the performance criteria, at least not when supply restrictions for the dry season problem were taken into consideration. Because of the inherent complexities of the WDS, it was not possible to meet all considered criteria with a unique solution; therefore, participant teams made trade-offs and decided on the criteria that were the most important, which is usual when solving real-world problems. For instance, one participant team decided to discard the number of DMA partitions, another group the demand similarity criterion, and another group the restriction on the maximum amount of water that may be extracted from one source in the dry season scenario. At the end, each group reached a solution that may or may not be feasible depending on the circumstances in which the solution is applied.

Another aspect that must be highlighted concerns the use of engineering judgment, which is an important part for most of the proposed solutions, if not for all of them. Regardless of the state-of-the-art method that was used to redefine a wide search space (something usual in WDS problems), important decisions were made considering engineering judgment. For instance, several groups adopted sophisticated optimization methods, such as ASO, PGA, nonsorting genetic algorithms (NSGA), multiobjective genetic algorithms (MOGA), PSO, SLC, or graph-theory based algorithms. However, at the end, a person or persons had to decide whether the optimization algorithm's solution was good enough to solve the problem because some parts of it cannot be modeled or simulated properly.

It is a known fact that some water utilities are reluctant to adopt newer technologies or methods because of their fears of how these new methods may degrade the hydraulic performance of their network given that it is not known how a particular method would affect their network. However, considering the results proposed by participant teams, it is possible to demonstrate that the reasons underlying the fears of implementing DMA partitioning may be wrong because it is possible to obtain good hydraulic performance and good pressure management. Although an effective DMA partitioning might be difficult to achieve, it was found that fulfilling all hydraulic requirements and preserving the safety of the distribution system (regarded as reliability in supply) is possible. This object was a main one of the competition, and it was interesting to witness how different teams proposed solutions to solve a complex but relevant problem. For this reason, it is interesting and encouraging to develop these types of competitions among the academic community, where the objective is and should be to improve the understanding of WDS design and analysis and to provide a discussion space to test new methods developed by academia, consulting firms, and water utilities.

Data Availability Statement

Some or all of the data and models used during the study may be available by request from the corresponding author of each participant team.

Supplemental Data

The E-Town original EPANET2 input file (.inp) is available online in the ASCE Library (www.ascelibrary.org).

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