



Division of district metered areas (DMAs) in a part of water supply network using WaterGEMS (Bentley) software: a case study

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Abstract

Designing of District metered areas (DMA) schemes is a key element in developing a technique for detecting and removing unreported leaks in a water distribution system (WDS) called active leakage control. The design of DMA is very specific to individual networks' hydraulic and often constitutes one area with pressure managed zones. This paper presents the division of a selected water supply network zone into DMA areas. Based on the spatial distribution of the flow rate and the geometrical structure of the network (routes, pipe diameters, existing gate valves) in the analyzed water supply zone, the main transmission trunks were separated (DN150 ÷ DN500 diameter range) and were excluded from the division into metering areas. DMA areas were separated from the remaining parts of the network, using the district metered areas module, supporting the division of water supply networks into metering zones, available in the WaterGEMS software by Bentley. The number of nodes in the area was 200 as the main criterion for separating DMAs. The separated areas were combined into 3 main DMA zones, in which the sum of the pipe lengths varied between 2500 ÷ 3800 m. For each of the DMAs, the water supply route was determined individually, seeking a one-sided inflow to the isolated area. In two out of three cases, this goal has been achieved. In the third case, it turned out necessary to provide two-sided water inflow. The analysis of the correct operation of DMAs was based on the hydraulic modeling of WDS.

Keywords District meter area (DMA) · Active leakage control (ALC) · Bentley WaterGEMS · Hydraulic modeling

Introduction

In 1980, the UK Water Authorities Association proposed the concept of district metered area (DMA) management methodology, which is used for monitoring leakages in water distribution networks (WAA 1980). Farley (2001) reported that the primary advantages of DMA management, in comparison with standard centralized monitoring and control, include improved system control, which reduces water losses, and facilitated pressure regulation. Water losses are encountered in all water distribution systems. They constitute one of the most severe issues that exploiters of water distribution networks have to deal with. They increase the operating and financial costs, as well as contribute to ecological and consumer problems (Suchorab and Iwanek 2019; Iwanek et al. 2017; Farley 2001). Generally, “water losses”

can be categorized into “apparent” and “real” losses. The former result from calibration issues, metering inaccuracies, or unauthorized use; in turn, the latter are the outcome of breaks and leakages, for instance (Eliades and Polycarpou 2012). Leakage is usually interpreted as the quantity of water escaping the pipe network via non-controlled action (Ofwat 2018). Generally, the water leakages occurring in distribution systems are divided into burst-related leakages and background leakages. The former correspond to structural pipe failures, whereas the latter represent the water which escapes, e.g., through faulty joints and cracks. Leaks may also occur in surface intakes and tanks. In open-surface water sources, water losses are primarily caused by evaporation and water leaking into soil. In tanks, objects with finite storage volume, the water losses are mainly caused by overflows or rust leaks in steel equipment or walls (Bentley Systems 2007; O'Day 1982; Puust et al. 2010). Leaks in distribution systems result from various factors, including internal or external pipe corrosion, mechanical damage, bad pipe connections, pipe defects, ground movement, high pressure in the system, pipe age, low ambient temperature

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in winter, etc. (Puust et al. 2010). Multiple methods of leakage detection have recently been presented in the literature. Lee and Yoo presented a software, a data-driven leak detection model using deep learning technology basing on inflow meter data, which showed more than 90% accuracy in immediate detection of the actual leakage (Lee and Yoo 2021). Nasirian et al. introduced a novel leakage detection method using ant colony optimization (ACO). The obtained results confirmed that optimization-based method can be effective in exact location and estimating the values of the leakages in a WDN (Nasirian et al. 2021). Seyoum et al. proposed a novel approach to household detection leaks by means of sound signal recordings. The approach consists of recording and detecting any abnormal situation in sound signals produced by water fixtures and appliances. The method, tested in laboratory conditions, resulted in a promising potential to reduce leakages by an easy-to-install and non-intrusive sensor (Seyoum et al. 2017). Soldevila et al. presented an integrated solution in which the leaks are detected by a sequential monitoring algorithm that analyzes the inlet flow and then validate each detection by an ad hoc statistical test. Experiments performed on a real WDN dataset showed that the proposed solution can improve the leak detection with the respect to methods already proposed in the literature (Soldevila et al. 2021). Puust et al. (2010) presented a comprehensive literature review of the leak detection and location methods.

Division of a water distribution network (WDN) into DMAs is considered as one of most cost-effective and efficient techniques of optimizing the operation of WDN in terms of reducing the real water loss rates (Puust et al. 2010; Kanakoudis and Gonelas 2014); hence, it is essential for the method for rapid detection and removal of hidden (unreported) leakages within WDS, known as active leakage control (ALC) (Gonelas and Kanakoudis 2016; Savic and Ferrari 2015). In numerous water supply companies, minimum night flow analysis is applied at every DMA in order to estimate the amount of water loss resulting from leakages (Thornton et al. 2008). The inflow is measured during the minimum water demand at every DMA, when the water consumption by customers is negligible, and the obtained readings are predominantly attributed to leaks. It is essential to perform an exact water demand analysis on the basis of 24 h water demand patterns. A significant role in detecting leakages play water system operators and performed by them observations of the flows in and out the DMA. These observations, usually of a manual character, depend on comparing flow values to the measurements from previous days or to certain thresholds. Nowadays, in times of a smart water supply systems, such comparison can be also done fully or semi-automatically, with the use of SCADA system and informatics software. Additionally, flow measurements values can be compared with results of numerical model calculations. If

the difference between current and historical or model flow values exceeds the acceptable level, an appropriate alarm is raised. In cases where there is no known reason of increased flow values, it can be associated with an unreported leakage which has occurred within a DMA (Thornton et al. 2008; Covas et al. 2006; Garcia et al. 2006). Nevertheless, small leakages may not be detected using this method, as a result of unpredictable variations in the demands of consumers, measurement noise, as well as seasonality and long-term trends. Hence, the active leakage control activities mainly involve a combination of pressure monitoring results and minimum night flow analysis, used to detect the possible deviations from ordinary WDN operation (Berardi 2016).

Efficient implementation of the active leakage control activities in separated hydraulic zones (DMAs) is a great challenge, especially in complex water distribution networks (e.g., Rogers 2005; Laucelli et al. 2017). The general guidelines for determining DMA areas have been developed by the International Water Supply Organization (IWA). The basic criteria to consider at the DMA division are as follows: minimum variation in ground level across the DMA; easily identified boundaries that are robust; size appropriate to number of burst to be identified; correctly sized and located meters; limited number of closed boundary valves; limited number of flow meters, optimized pressure to maintain the customer standards of service and to reduce leakage (IWA 2007).

The DMA designation usually involves the trial-and-error approach, using digitized maps of the water supply network with ground contours. This process should account for the existing boundaries, topography, natural features, including railways, rivers, major roads, etc. (Karathanasia and Papa-georgakopoulou 2016). Numerous methods of DMA optimization and determination have been developed in the last few decades. Tzatchkov et al. (2006) employed the technique involving the use of the graph theory to obtain the number of independent sectors within a network layout, the set of nodes belonging to every sector as well as disconnected nodes, and the source to node contribution. In turn, Kadu et al. (2008) presented a modified genetic algorithm (GA) with reduction in search space which randomly uses basic operators and their derivatives. Diao and Zhou (2013) demonstrated another approach, in which a hierarchical decomposition of the water distribution system into communities is applied to create DMA boundaries in WDSs. Community structure gathers vertices together, such that there is a higher density of edges within communities than between them. Therefore, the obtained structure of communities representing the DMAs can be used to identify the layout of the WDS. In addition, combined (hybrid) methods were proposed by some authors (e.g., Perelman and Allen 2015 2010; Eliades et al. 2014; Di Nardo et al. 2015; Brentan et al. 2017; Diao et al. 2013; Chatzivasili et al. 2019). Chatzivasili

et al. (2019) showed a two-stage hybrid approach providing optimal division of a WDN into DMAs, contributing to improved pressure and water age. The network was divided into smaller areas by means of the geometric partitioning method based on recursive coordinate bisection (RCB). Then, the Student's t-mixture model (SMM) was used for each of the areas, achieving an optimal placement of isolation valves and network separation in DMAs. Both stages were implemented in a MATLAB environment using the EPANET toolkit. Gonelas et al. (2017) optimized the DMAs formation using combined MATLAB and EPANET software tools and assuming the operating pressure of the WDS and the chlorine residual concentration as the design criteria. The former algorithm determined the most appropriate pipes to be closed, thus optimizing the operating pressure within the system to reduce real water losses. In turn, the latter algorithm employed gas optimization, producing all the possible combinations of closed pipes in order to optimize the chlorine residual concentration.

The aim of the paper was the division of DMAs in a part of an existing water supply network with a complex geometrical structure. The division of DMAs was carried out using commercial WaterGEMS software by Bentley, which comprises a DMA-Tool used for this purpose. Additionally, the analyses were performed with a calibrated hydraulic model, which served both for a preliminary analysis of the water supply network operation and adoption of main assumptions for its division. It was also used for evaluating the correctness of the DMA division. The conducted simulations revealed the irregularities in the operation of the water supply network. The division into DMAs constitutes the first step toward the implementing the monitoring of water flow rate and pressure in these areas, which are managed by the Water Company.

Object description and research methodology

The division into DMAs was performed in a fragment (zone) of an existing water supply system of a city with approximately 30 000 inhabitants, located in a mountainous area. The analyzed zone is characterized by the oldest water supply infrastructure, with about 40% water loss index of the system input volume. The material structure of pipes is highly diversified, including asbestos cement pipes (AC), cast iron, steel, polyethylene (PE), and polyvinyl chloride (PVC), while the pipe diameters range from 40 to 600 mm. The length of pipes (excluding connections) amounts to ca. 260 km. Figure 1 shows the water supply network with a marked fragment which was divided into DMAs.

The analyzed fragment of the water supply network is characterized by relatively low differences in terrain

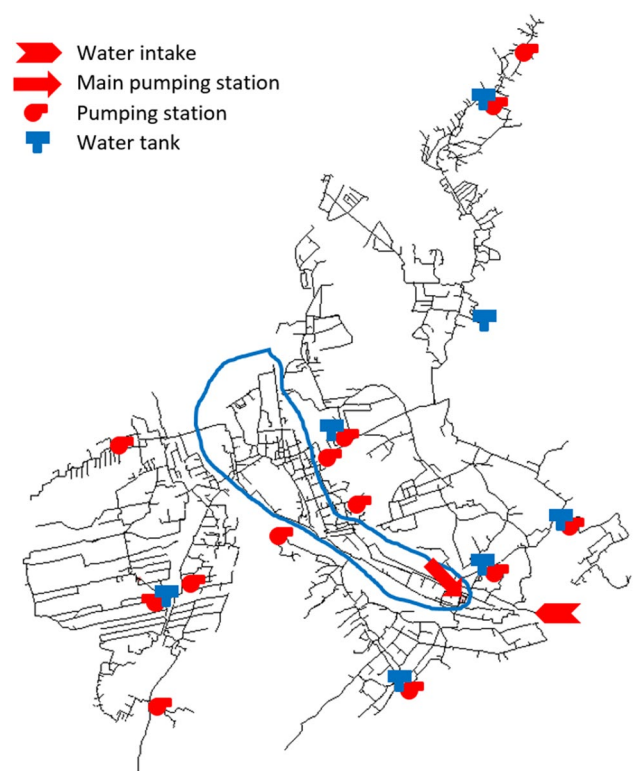


Fig. 1 Scheme showing the geometric structure of the water supply network along with the location of the intake, pumping station, and water tanks. The blue line designates the analyzed area

elevations (compared to the rest of the network), ranging from 330 to 370 m a.s.l., which is an important criterion taken into consideration while designating the DMAs. The zone consists of pipes transporting water directly or indirectly to a substantial part (about 2/3) of the entire water supply network. The division of DMAs was performed using commercial WaterGEMS software by Bentley (Bentley Systems 2007). The DMA-Tool module, available since version 10.02.01.06, was employed for an automatic division of the selected part of the water supply network into DMAs. Prior to the DMA-Tool application, the spatial distributions of flow rate and the geometric network structure (pipe locations and diameters) were analyzed and the segments which can be described as “transmission” (marked in red in Fig. 2a) were distinguished. Transmission pipes are an essential part of the water supply network structure—water distributed by these pipes is supplied to external zones of the WDS. The correct operation of these segments is vital for the proper functioning of the entire water supply system. These are predominantly water mains (with diameters of over DN300 mm), but also pipes with smaller diameters. The diameters of the marked fragments are within the range of DN150 mm to DN500 mm. The task of the remaining pipes is twofold: supply water to recipients as well as supply the designated DMAs and other zones of the water supply system. Taking

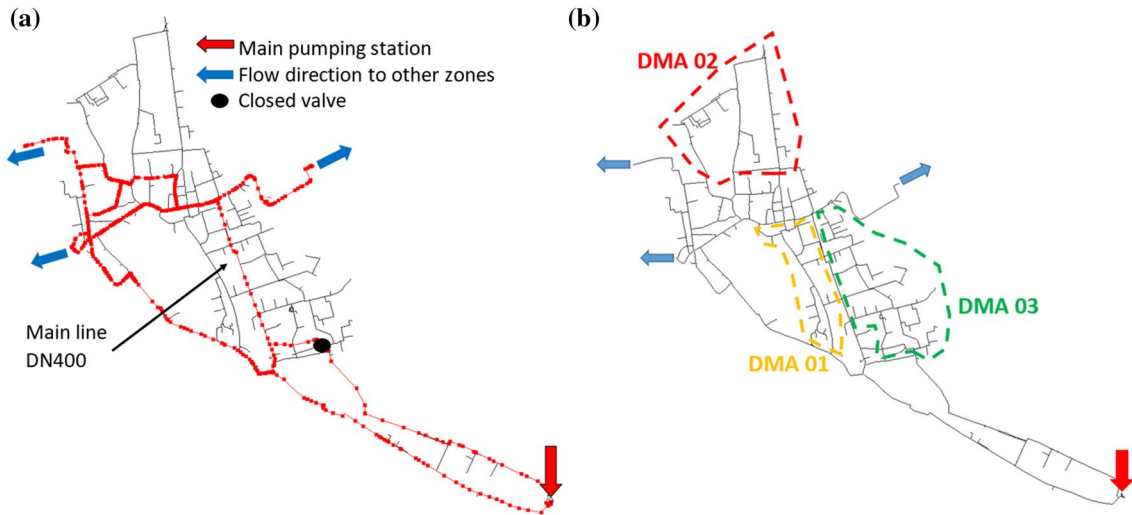


Fig. 2 a “Transmission” pipes and b preliminary division into DMAs

into account the main criteria for DMA division, such as separation from transmission pipes, one-way supply of the areas, comparable number of nodes, and similar elevations, a preliminary division into 3 areas was proposed: DMA 01, DMA 02, and DMA 03, which were marked with dashed lines in Fig. 2b.

Prior to the DMA-Tool application, the status of the sole closed isolation valve in the analyzed zone was changed to *Open*. Since the created DMA division changes the flow distribution in the zone, the existing flow barriers (closed isolation valves) should be removed (their status should be changed into *Open*). In order to determine the initial objects which could constitute DMA boundaries, the *Initialize DMA Boundary Status* box should be opened (path: *Analysis* → *More* → *District Metered Areas* → *Assign DMA Status* → *Initialize DMA Boundary Status...*)—see Fig. 3a. By default, all boundary objects (closed pipes, pipes with closed isolation valves, pumps/pump batteries, valves: PRVs, TCVs,

GRVs) constitute the DMA boundary set by the program. The user can change the DMA status from *Boundary* to *Boundary Candidate* if they consider the possibility that a given object could not constitute a DMA boundary. The next step involved assigning the *Transmission* status as *DMA Status* to the transmission segments distinguished in Fig. 2a. The *DMA Status* attribute is a parameter characterizing a given segment, which determines the purpose of a given object in the course of DMAs division.

In order to employ the DMA-Tool module for the DMA division, the *Compute* option needs to be selected. The division criterion needs to be determined at this stage: *Target Number of Nodes* or *Target Pipe Length* (Fig. 3b). At first, it is recommended to define a small number of nodes, which can then be increased if required. This enables to observe the changes in the boundaries of particular DMAs. If the results prove to be unsatisfactory, the adjacent DMAs can be merged into a larger area. In the considered case, the

Fig. 3 a *Initialize DMA Boundary Status* dialog box and b *DMA Settings* dialog box

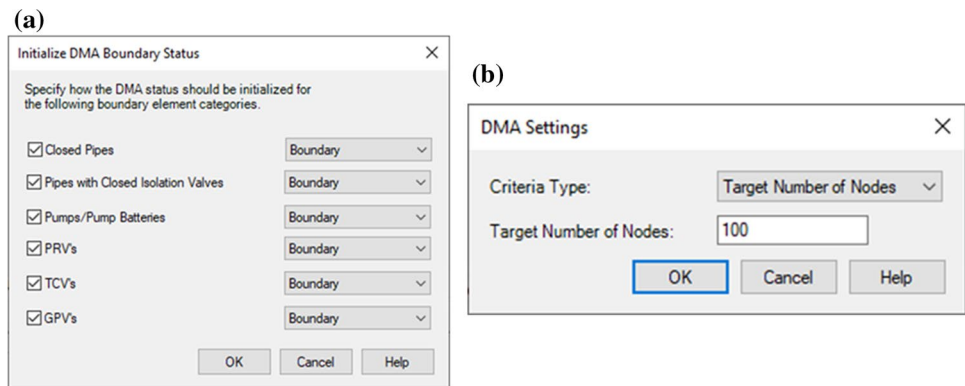




Fig. 4 The analyzed zone divided into DMAs generated by means of the WaterGEMS software (DMA-Tool)

division began with 100 nodes (Fig. 3b), subsequently increased to 200.

Figure 4 presents the division into DMAs performed with the DMA-Tool module. The pipes with the *DMA Transmission* status (marked with black lines) were omitted in the process. The software interprets each fragment of the network which can be isolated as a separate area, aiming to ensure that the size of particular fragments is as close to the

desired one as possible (in this case—200 nodes). However, this is not always possible; sometimes, there are fragments in the network which should not be considered DMAs, e.g., separate water households connected to transmission pipes. In the analyzed case, the software indicated 81 areas which could be isolated, but only 4 of which (marked with pink, green, dark green, and purple color in Fig. 4) met the assumed criterion of 200 nodes. Additionally, the fifth indicated area comprises 168 nodes. The total length of pipes in 5 largest areas ranges from 2.4 to 3.8 km. The remaining areas were ignored in the further analysis, as the number of nodes within them did not exceed 50. These separate segments of the WDN cannot be identified as a DMA (e.g., household connections, pipes between tank and pump station) and therefore the further analysis focused only on 5 biggest zones generated by the software.

Figure 5 presents the result box of the DMA-Tool module with designated areas in descending order in terms of the total pipe length. On the basis of the obtained results, the adjacent areas of the 5 biggest zones were merged together to achieve preliminary DMAs presented in Fig. 2b. The merging process enables forming larger DMA from smaller connected ones. For this purpose, the area for merging was selected (starting from the first area in the table, i.e., 69), and then the DMAs merging was initiated (path: *Assign DMA Status* → *Merge Adjacent DMAs*) (Fig. 6).

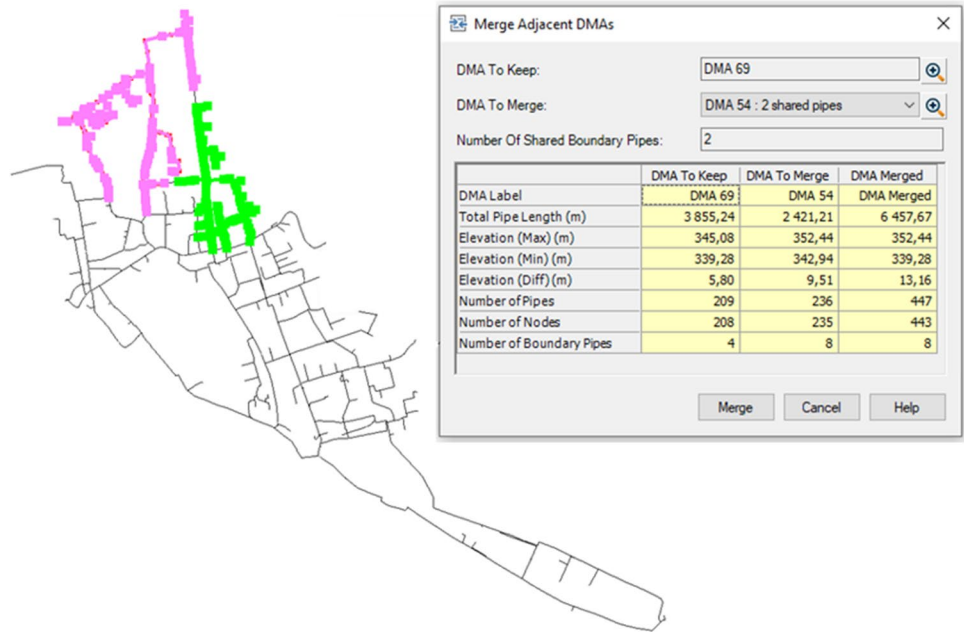
Figure 6 presents the dialog box shown in the process of merging areas 69 and 54 (DMA Label in accordance with Fig. 5.) into a single area—DMA 02. The resultant area comprises 6.5 km of pipes and 443 nodes. The difference

Fig. 5 DMA-Tool result box

| DMA Label | Total Pipe Length (m) | Elevation (Max) (m) | Elevation (Min) (m) | Elevation (Diff) (m) | Number of Pipes | Number of Nodes | Number of Boundary Pipes | Color |
|-----------|-----------------------|---------------------|---------------------|----------------------|-----------------|-----------------|--------------------------|------------|
| DMA 69 | 3 855,24 | 345,08 | 339,28 | 5,80 | 209 | 208 | 4 | 55,128,255 |
| DMA 23 | 3 477,10 | 365,00 | 349,20 | 15,80 | 258 | 257 | 4 | 255,0,255 |
| DMA 77 | 3 180,25 | 351,97 | 345,09 | 6,88 | 268 | 268 | 7 | 0,255,0 |
| DMA 57 | 2 858,62 | 358,55 | 348,60 | 9,95 | 167 | 168 | 5 | 0,128,0 |
| DMA 54 | 2 421,21 | 352,44 | 342,94 | 9,51 | 236 | 235 | 8 | 0,255,0 |
| DMA 67 | 612,59 | 344,57 | 341,85 | 2,72 | 38 | 39 | 2 | 55,255,128 |
| DMA 74 | 361,56 | 345,84 | 344,58 | 1,26 | 41 | 42 | 2 | 255,255,0 |
| DMA 36 | 301,75 | 340,95 | 340,88 | 0,07 | 1 | 2 | 1 | 0,255,255 |
| DMA 34 | 291,75 | 348,46 | 343,61 | 4,85 | 24 | 25 | 3 | 28,255,255 |
| DMA 27 | 202,56 | 360,03 | 358,19 | 1,84 | 10 | 11 | 1 | 28,128,128 |

| Label | ID | Type |
|-------|------|----------|
| J-283 | 9264 | Junction |
| 70023 | 608 | Hydrant |

Fig. 6 Dialog box appearing while merging the areas 69 and 54 into a single area—DMA 02



in elevation amounts to 13.16 m (from 339.28 to 352.44 m a.s.l.), this area is delimited by 8 boundaries. The areas 23 and 57 were similarly merged into DMA 03. The created area includes 6.3 km of pipes and 425 nodes. The difference in elevation equals 16.40 m (from 348.60 to 365 m a.s.l.) and the area is delimited by 7 boundaries. By employing the same methodology, the fragment of the network on the left side on the DN400 main (Fig. 2a) was assigned to the preliminarily designated DMA 01, comprising 3.2 km of pipes and 268 nodes.

Following the merging of selected areas into DMA 01, DMA 02, and DMA 03, the boundaries of particular DMAs were designated. The DMA-Tool module does not use isolation valves, but indicates the boundary pipes. The closure of a pipe is performed via the isolation valve—therefore, the isolation valves which enable this closure should be located in the pipes indicated as boundaries of particular DMAs. For this purpose, the given DMA should be selected and the *Boundary Elements* tab clicked (see Fig. 7); then, the objects included should be highlighted. Figure 7 presents the pipes constituting the boundaries of DMA 02, marked as red dots. The boundaries for DMA 01 and DMA 03 were designated in a similar manner.

The final step in DMAs division involved selecting the water supply paths for these areas. On the basis of the distribution of diameters the gathered knowledge on the analyzed water supply system and a single supply segment per DMA were proposed (Fig. 8, blue arrows). These included a DN200 pipe for DMA 01, a DN250 pipe for DMA 02, and a DN150 pipe for DMA 03. Owing to the one-way supply, the measurement of water supplied to the given area can be carried out in a single installation chamber.

Discussion of results: verification of the correctness of the water supply network operation following division into DMAs

Following the division into DMAs, establishing boundaries, and determining the directions of water supply for each area, the analysis of the water supply system operation was carried out using a calibrated hydraulic model developed in WaterGEMS. The correctness of the water supply system network operation was considered in two major aspects: a) sustaining the transmission character of the zone, b) ensuring the proper hydraulic conditions in divided DMAs. These aspects were verified basing on the results of a 7-day simulation, especially considering the water flow rate and flow intensity during the maximum demand hour. Additionally, the filling processes of tanks located outside the transmission zone were examined.

The calculations indicated no issues in the operation of DMA 02, which was located outside the transmission area of the analyzed zone. Closure of DMA 02 with isolation valves and supplying it with a DN 250 pipe ensures both the appropriate pressure values in nodes as well as unhindered supply of water to recipients. Division of DMA 01 does not cause disturbance in the operation of the water supply system, but slightly reduces the throughput, which is reflected in a slower filling of the water tank located in an adjacent area. The graph of water level in this tank is presented in Fig. 9. It can be noticed that the filling-emptying stages of the water tank are time phase shifted. Moreover, on 6th day of the simulation there is a significant disturbance in water filling process. The blue line (water tank level after division

Fig. 7 Pipes constituting the boundary elements of DMA 02

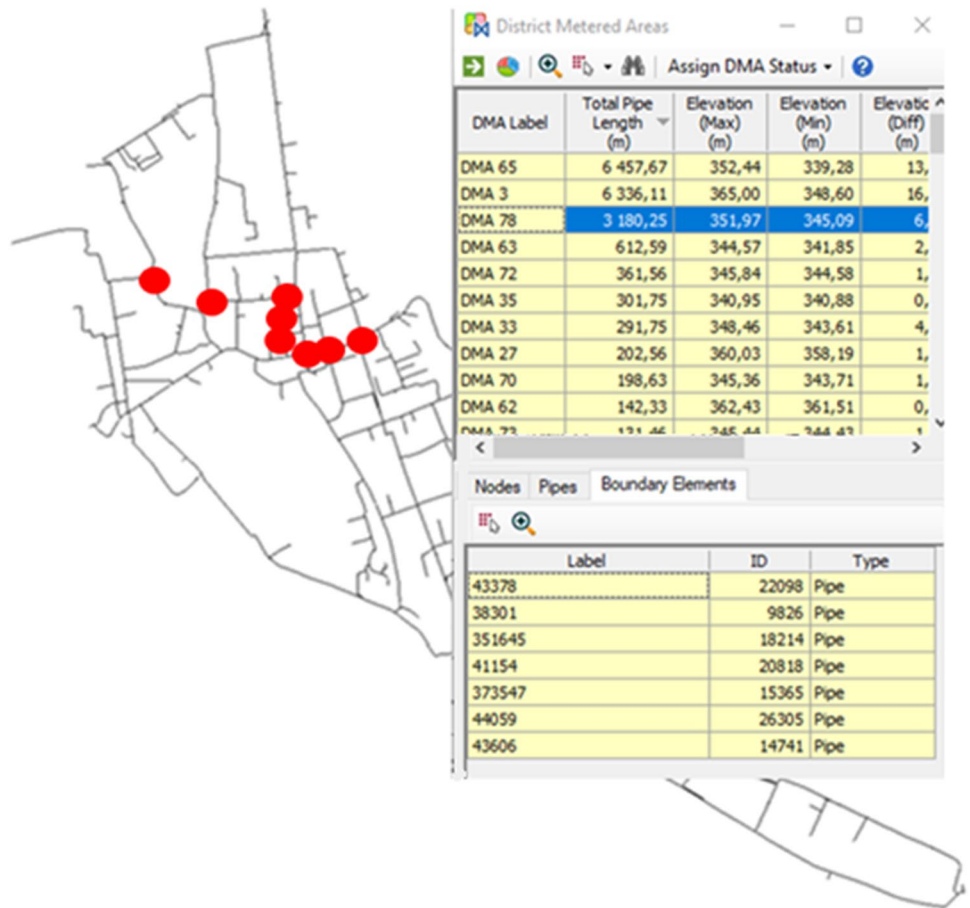


Fig. 8 Directions of DMA water supply (blue arrows). The transmission segments were marked in red, whereas the new pipe supplying DMA 03 was marked as a green arrow

into DMAs) is below the acceptable minimum level—the tank is unable to fill up due to the limitations in water transmission from the central WDS zone.

However, the main problems were observed with the division of the DMA 03. Calculations revealed a significant reduction in the flow of water into this area, resulting in insufficient pressure values in some locations. This means that supplying the entire DMA 03 by means of a single pipe with the diameter of DN150 is insufficient. Therefore, a double-pipe supply of DMA 03 was proposed. A pipe with the diameter of 160 mm with an isolation valve set to *Open* was selected as the second supplying pipe. Figure 8 shows the directions of DMA water supply, along with the transmission pipes and a new pipe supplying DMA 03 (green arrow). Additionally, in order to ensure adequate pressure in DMA 03, the modernization of the main pumping station (its location is marked in Fig. 1a) involving increasing its output from 400 to 430 m³/h and increasing the pumping pressure from 20 to 25 m H₂O, was proposed. After the second supplying pipe and pump station modernization, the simulation studies showed that no low pressure warnings were generated following the implementation of these changes. However, it should be taken into consideration that the increased pressure may contribute to greater water

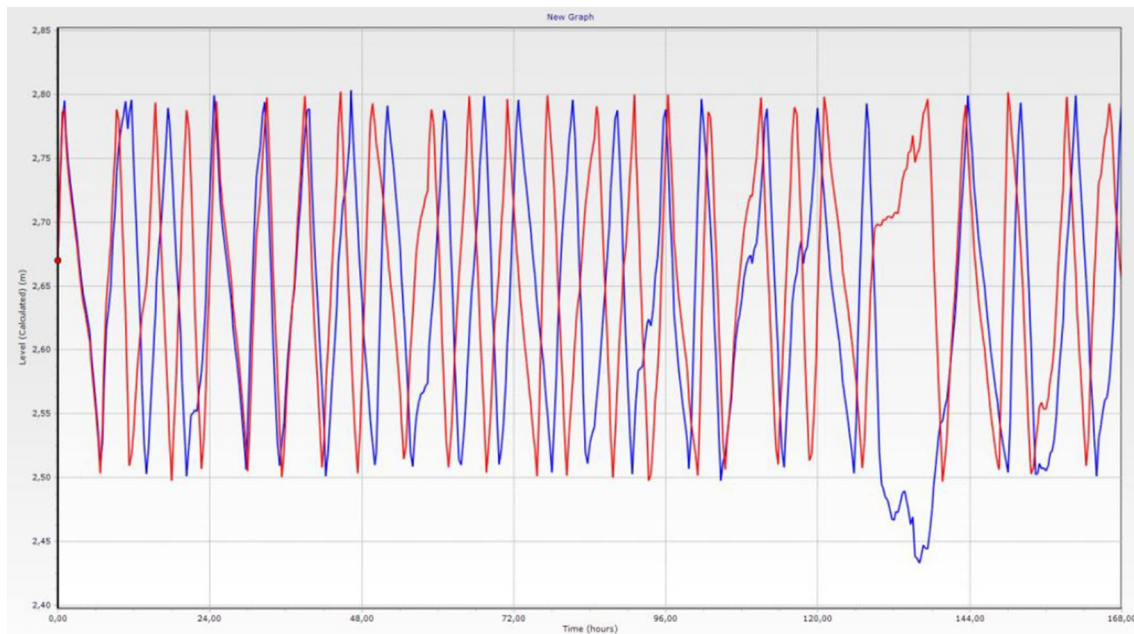


Fig. 9 Water level in one of the water tanks (red line—before DMAs division, blue line—after DMAs)

losses due to the presence of old infrastructure in the analyzed zone. Therefore, the modernization of the pumping station should involve improving the technical condition of pipes within this zone.

Pump station modernization resulted also in maintaining the transmission character of the zone, what can be observed in water tank level shown in Fig. 10. The filling-empting

stages are undisturbed, the minimum water level is not exceeded and there are no problems in filling water tank on the 6th day of the simulation. Basing on obtained 7 days simulation results, it can be claimed that the division of the analyzed zone into separate DMAs together with modernization of main water pump station parameters ensures the continuity of water supply to all recipients and water tanks.

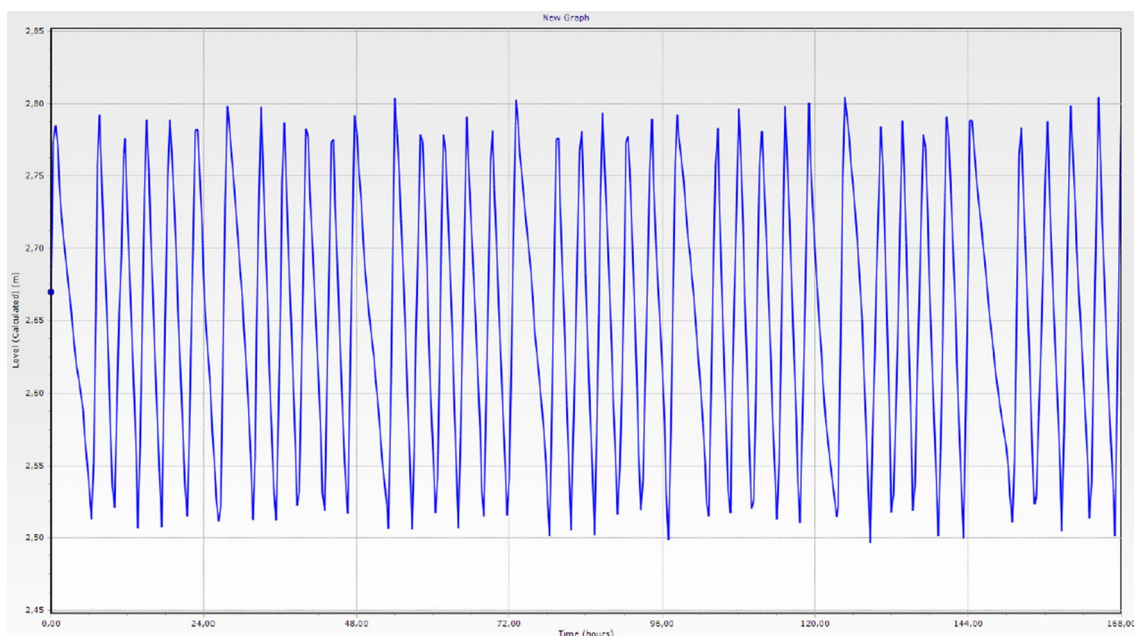


Fig. 10 Water level in one of the water tanks after the modernization of the main pump station

Conclusions

Division of DMAs in the existing zone of municipal water supply network was carried out using WaterGEMS computer software with the DMA-Tool module. The automatic division of DMAs facilitated and accelerated the process, but also significantly overestimated the number of DMAs. The software created as many as 81 areas, including 5 major ones, therefore it was necessary to modify the obtained results. The indicated areas were merged into three main DMAs—DMA 01, DMA 02, and DMA 03.

The correctness of the water supply system operation following DMA division indicated that DMA 01 and DMA 02 cause no disturbances in the network operation—the flow rates and pressure values in particular areas ensure unhindered supply of water to recipients. In the case of DMA 03, the computer simulations indicated the issues with maintaining appropriate pressure at some recipients and difficulties in supplying the adjacent water tanks. Therefore, double-pipe water supply and modification of the pumping station operational parameters were proposed in this area.

On the basis of the conducted simulations, it can be stated that the increased pressure greatly improved the hydraulic conditions not only in DMA 03, but also in the entire system. Due to the poor technical condition of pipes in the analyzed part of the network, the increased pressure may result in significant water losses. Hence, the replacement or repair of the existing pipes is recommended. Installation of pressure-reducing valves in the locations supplying each DMA is also a viable solution.

Author contributions BK contributed to conceptualization and writing—original draft preparation. PS contributed to methodology and writing—review and editing. DK contributed to data analysis and formal analysis.

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Availability of data and materials The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Not applicable

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