WATER SUPPLY NETWORK ZONING PROCEDURE DEVELOPMENT CONSIDERING LOCAL CONDITIONS

Aram Sahakyan
National University of Architecture and Construction of Armenia, Yerevan, RA

Abstract: *The methods of performing zoning implemented in the water supply networks of various settlements in RA have been continuously improved over the past years and are currently carried out by a procedure developed by us, which has increased the efficiency of the water supply system operation.We have implemented this to increase the efficiency of the water supply system. There are several principles for the zoning of the water supply network's concepts in the literature, but using the current techniques only reduces the volume of water provided to the zone by 8 to 10 percent and the time of supply by a fixed amount (not around the clock). Additional investigation led to finding the causes of zoning's poor effectiveness, the shortcomings of the design, insufficient level of network research, application of incorrect principles of zoning and pressure management. We developed the methods discussed in this paper to resolve the aforementioned problems. Analyzing the results of multi-year studies and considering the current technical situation of the distribution network, we recommend continuing the zoning of the networks for the current stage until the night-time consumption of the zone is less than half of the daytime consumption.*

Keywords: *water supply network, water supply network zoning, leakage, night water consumption, network zero pressure test.*

Aram Sahakyan
E-mail: sahakyan.aram@nuaca.am

Received: 17.01.2023
Revised: 07.02.2023
Accepted: 22.02.2023

Introduction

The requirement for zoning of the distribution network arises in mountainous conditions when there is a significant difference in levels within the boundaries of the settlement. Both gravity and pressing systems (reverse zoning) may require zoning [1,2].

When high-rise multi-residential buildings are constructed in areas where low-rise buildings are already present or when the high-rise buildings' absolute height exceeds that of the low-rise buildings within the water supply zone's boundaries, zoning becomes crucial. Therefore, to increase the controllability of the distribution network, it is necessary to implement effective zoning of the network, i.e., to transform the network into hydraulically separated zones that are isolated from one another. Isolation must be implemented by installing existing or new valves, which will be closed during the regular operation of the water supply network, but can be opened if necessary. In mountainous areas, it is advisable to use vertical zoning in a sequential or parallel scheme.

Many automatic network zoning approaches have recently become widely used with specifically created computer programs (hybrid approaches for the automatic partitioning of a water distribution network, spatial analysis zoning approach, semi-supervised method etc.). However, the application of these techniques is unworkable with an existing network that is worn out, elementally constructed and reconstructed, or fragmented. Our original research showed that some additional problems arise when creating zones using existing weathered, prefabricated, reconstructed, or fragmented networks. Thus, after zoning Arabkir zone 1, Kievan, Gulbekyan, and Keri streets, it was found that the amount of water supplied to the zone decreased by only 8%–10%, and the 8-hour duration of supply was 12 h instead of the planned round-the-clock.

Because the designed pressure wasn't maintained, accidents happened more frequently. Additional investigation led to finding the causes of zoning's poor effectiveness:

- the shortcomings of the design,
- insufficient level of network research,
- application of incorrect principles of zoning and pressure management.

We developed the methods discussed in this paper to resolve the aforementioned problems.

Because of the analysis of the original research and operation data on the water supply network, as well as the international experience applied in similar conditions and the study of the existing literature, the zoning works carried out in the water supply network of different settlements of RA have been improved and are currently being carried out efficiently according to a procedure developed by us. The principles of water supply network zoning are found in several versions of the literature currently in print. Many automatic network zoning approaches have recently become widely used with specifically created computer programs. However, the application of these techniques is unworkable with an existing network that is worn out, elementally constructed and reconstructed, or fragmented.

Different models have been proposed, based on classic optimization methodologies or on meta-heuristic approaches [3-7].

The optimal design of DMAs as part of a Decision Support System (DSS) for reducing the water losses has been addressed only recently in the literature. Some authors have proposed hybrid approaches for the automatic partitioning of a water distribution network, based on both meta-heuristic algorithms and on applications from the graph theory [8,9].

The proposed models mainly focus on the preservation of the hydraulic reliability of the network, while less control is allowed on the costs of the provided solutions [10].

Sempewo et al. [11] developed a spatial analysis zoning approach based on the METIS graph partitioning tool [12].

The proposed technique follows the analogy with the distributed computing methodology of equally distributing workloads among processors. However, as stated by the same authors, although the method results effective in the demarcation of contiguous districts, the quality of the provided solution degrades when considering multi-objective partitioning, and uncertainties are produced when increasing the number of DMAs.

Herrera et al. [13] proposed a semi-supervised method named multi-agent adaptive boost clustering. This complex technique considers both the WDN features (e.g. node elevations and demands) and the economic issues (edge cut = number of pipes to be intercepted) for the partitioning of the network. Nevertheless, the procedure is only applied to cases in which the number of DMAs is lower than the number of supply nodes.

More recently, [14] have introduced an approach for automatic creation of DMAs based on the hierarchical community structure of the WDN. In this study, the selection of the feeding lines for the DMAs is made through an iterative selection method based on a sensitivity analysis. The methodology was tested on a very large network with reasonable computing times, but the results showed high sensitivity towards the assignment of the input parameters.

A comprehensive description of the possible objective functions for the problem can be found in Gomes et al. [15].

The two-step approach proposed by the authors consists of a preliminary partitioning of the WDN into suitable DMAs through the application of the design criteria and graph theory concepts, i.e. the Floyd-Warshall Algorithm (FWA). Next, Simulated Annealing (SA) is used for the localization of entry points and of boundary valves, but also for planning the reinforcement/replacement of pipes in the network. Although the results have resulted satisfactory, the global optimality of the solution is not ensured by the SA. Hence, despite the newest contributions, further developments seem required about this topic [16].

Among the available approaches for pressure management, the use of District Metered Areas (DMAs) also allows for a more accurate localization of the leakages in the water distribution network, which is achieved by monitoring the input and the output discharges for each district. Nowadays, this approach is widely used in practice, but its application is still largely entrusted to the experience of technicians [10].

According to the proposed principles, to increase the zoning and manageability of the water supply network, it is necessary to create hydraulically isolated zones with up to 3000 subscribers in the settlement. Since the zoning is carried out under the conditions of the existing system, the procedures developed during the design and reconstruction work consider the features of the existing system: difference in characters; dictating characters of the day regulatory reservoirs; location and volumes; diameters of the existing pipes; height of the buildings; population density; etc.

It is suggested to remove the inner rings of the zone by temporarily converting the ring network within the presented zone boundaries into a dead-end network using valves and separate sectors. Magnetic flowmeters and pressure recording sensors should be installed on the feeding pipes. It will allow for assessing the water balance within individual zones, determining the amount of unaccounted water, and discovering its nature and location [17].

These investigations aim to calculate how much water enters each zone and compare it to how much water is received based on the number of subscribers. By creating water supply sectors with one-way flow and an exact number of subscribers, it is possible to estimate the amount of unaccounted water in the presented zone. During the zoning (design and construction) of the existing water supply network, it may be necessary to apply the following procedures: changes of water sources (spring, aqueduct, daily regulating reservoir) in zones or sometimes in entire districts, change of design and/or operating hydraulic regimes of water pipelines, converting the ring network temporarily into dead-end sectors with separate one-way flow, loss detection and elimination, installation of pressure regulators at required points, decommissioning or replacing backyard pumping stations with smaller capacity pumps, as well as a grouping.

Before the implementation, it is crucial to perform studies and designs at a high level through experienced engineering solutions because zonings require financial investments and impact the quality of services offered. However, experience shows that it is almost impossible to have a final zoning project, so during the execution of the works, there is a need to review the scope of the study.

Materials and Methods

Design and implementation of a water supply zone

Before starting the zoning, it is necessary to analyze the problems and data recorded during the operation, define the registration procedure, create a working group, acquire the needed equipment for measuring and control, and eliminate obvious (visible) leakages.

The following sequence of work has been developed for the design of zones and their implementation (construction).

1. The existing water supply distribution network is divided into separate zones through valves on the plan. During this demarcation, it is necessary to consider the possibility of creating optimal pressure regimes in the zones and excluding the dead sections in pipelines.
   Limiting valves should be installed just away following the connections of relatively large volume of water users to prevent the creation of dead-end areas (no flow or small flows), as the valves turn the pressure zone into a dead-end network. Water quality degradation is possible in areas with a low water flow rate [1]. As mentioned above, to ensure the controllability in the pressure zone, it is necessary to create sectors with a smaller number of subscribers. According to the results of the studies, the zone should include 500–3000 subscribers, depending on the level of leakage, the development characteristics of the district,

the applied methods of leakage control, and hydraulic conditions. The water supply zone may serve 3000 customers in densely populated places, as it is in the settlement's city center. However, in these cases, it is challenging to distinguish minor breaks separated from flow data recorded at night, making it more difficult to pinpoint their place. However, by temporarily closing valves, large water supply zones can be divided into sub-sectors of two or smaller sizes. In this situation, extra valves might need to be placed during the water supply zones' design phase.

2. The power source is determined based on the case of providing an uninterrupted water supply to the facility in the most dangerous (critical) conditions of the specified area. In design practice, these zone feeding options are possible:
   1) the zone may have one or two power sources: an aquifer or a reservoir,
   2) zoning work can be carried out sequentially: here, the second zone receives water from the first zone in a transit way (Fig.).

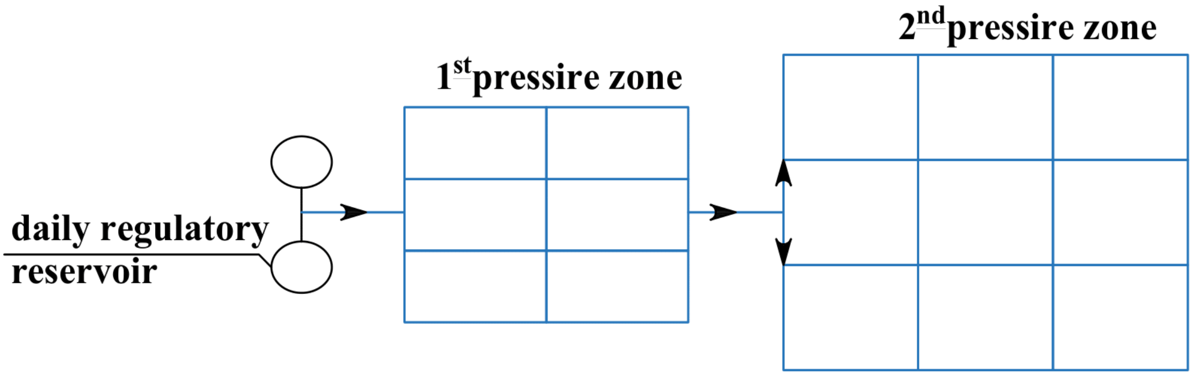

Fig. *Sequential zoning scheme*

3. It is planned to close off the valves on all border feeding lines during the hydraulic isolation of the divided zones, leaving only the targeted feeding line. To guarantee total isolation, sometimes required to install new valves. Small-scale maps of the distribution of water lines, information from operating staff, and existing hydraulic data are employed at this stage of contour limitation of the water supply zone design. In establishing the boundaries of the water supply zones, besides the general design criteria, the following conditions should be considered:
   - make the most of the feed source's power or pressure (day regulating reservoir, aqueduct) position. In this case, area and topography may dictate sequential zoning using existing pipelines.
   - any transit aqueducts or water lines feeding other zones are avoided as much as possible while drawing the boundaries of a zone,
   - if possible, the diameter of the water line supplying the zone should not exceed 300 mm to avoid high financial costs and technical complications associated with the flow measurement unit installation,
   - to ensure that research can take place, the area should have a constant supply of water.

4. "Zero tests" is used to verify the compliance of the design works with the completed reconstruction works. It provides the implementation of the following conditions:
   - inspecting the installed flow meter for accuracy,
   - checking the functioning (hermetic) of the boundary valves,
   - detection of hydraulic connections between neighbouring zones,
   - inspection and assessment of changes in the quality of water supplied to customers in the reconstructed zone and neighboring zones,
   - check for excess pressures.

Zero pressure test procedure

Zero pressure testing is carried out at night, between 1^{00} and 5^{00}. In order to detect hidden connections between zones, data recording devices (loggers) are connected to the cost meters of the lines feeding the tested and neighboring zones.

The tightness of the boundary valves and the existence of any hidden connections are then assessed by closing the boundary valves. For the situation assessment, it is also necessary to temporarily install the automatic pressure recording devices at defined points in the network during testing. After that, the valve supplying the zone is closed, and if there is no significant pressure drop within 5 minutes, any hydrant in the lower part of the network is opened, reducing the pressure to zero. The pressure in the water supply zone must be zero when the hydrant is closed; otherwise, another power source that wasn't considered during the design may exist, or the tightness of any boundary valve that is audibly checked may not be maintained.

The zero pressure tests are a crucial procedure for determining whether the water supply zone is hermetically sealed, so the aforementioned investigations must be continued until the experiment's successful completion is guaranteed. It may take up to a year to get positive results from the zero pressure test, depending on network characteristics (zone size, number of subscribers, population density, and the ratio of private and multi-residential buildings).

The described measures are necessary because proper zoning was not carried out during the design and construction of existing water supply networks. Besides, the circumstance that the drawings created during the construction of the water supply system do not match the actual situation made the design and implementation of the zone more challenging.

Failure detection and elimination are carried out to reduce power losses. For this phase, we determined that the night-time costs of the zone should not exceed 50% of the daytime cost. Finding and eliminating hidden leaks can also take several months.

Day and night flow is recorded after these functions' completion and is necessary for benchmark indicators to evaluate the effectiveness of zoning (redevelopment), which must be monitored and maintained during operation.

The precise estimation of the zone's night flow and its ongoing regulation, as well as data updates, are of particular importance required for the following functions:

- continuous maintenance of the water supply zone's hydraulic isolation. There is often a conflict of interests between the operating units and the zoning group: opening of boundary valves, disturbance of zone boundaries, etc. Such cases must be monitored and prevented until their elimination,
- regularly updating the number of subscribers,
- modernization and improvement of data acquisition methods and technologies,
- leak detection and elimination in a planned manner,
- regular analysis of received data.

Conditions for creating a sector (dead - end network) during the design

Because of the formation of sectors within the borders of a separate zone, the existing ring network turns into a dead-end having a one-way supply. Hydraulic calculations are required to verify the transmittivity and pressure losses of the sections to maintain the water supply of the dead-end network.

For this purpose, a calculation scheme for the dead-end network has been created. It is divided into calculation sections, where the directions of water flow are noted, and the actual outputs in the sections are measured.

In contrast to the well-known method for calculating the dead-end network, during the conducted studies, the outputs obtained through experimental measurements are taken as the calculation output for each section based on the maximum actual water demand. When choosing the endpoint for constructing pressure lines based on the measured outputs, not only the distance and relief but also the required pressure at that point, considering the height and location of the buildings, are considered.

After measuring the outputs of the designed dead-end network segments, the network transmittivity condition is checked. For this purpose, the pressure losses occurring in the sections are determined by the formula $h_l = SQ^2$, using F.A. from Shevelyov's tables [3], based on which the free pressure lines of the network are built to have the pressure magnitude at all points of the selected calculation direction. Free pressure lines are installed in every direction possible to assess the pressure at the examined network's sites. In the event of a problem providing pressure in the subzone of the designed dead-end network, based on specific conditions, it can be solved by the following options:

- by over-correcting the pressure regulators or opening the compressed valves on the supplying water pipe (if available),
- the excess pressure regulation increased the pressure in the initial part of the considered sub-zone in the neighboring sub-sector,
- to change the power source of the zone that will provide the required pressure or apply another zone scheme,
- pressure losses in the specified sections reveal the significant leaks by finding and fixing leaks in any section or sections. Therefore, it may be found that the cause of the pressure loss is a hidden local resistance (unknown compressed valve, presence of a gasket, or blockage),
- by increasing the diameter of a specific network section if the pressure line in that section has a steep slope,
- by installing local pumps if the pressure is insufficient for a few high-rise buildings.

The last two options are advisable to use in case of economic feasibility. It should be added that when performing zoning, the need to increase the diameter or install a pump arises in rare cases because the diameters of pipelines built in the Soviet era are chosen with a high stockage.

The priority of the implementation of distribution network zoning

Because of the zoning processes' financial and technical requirements, it is impossible to carry out operations simultaneously in all planned zones. Instead, priority is given to the zones with the highest leakage levels. Based on the technical condition of the distribution network of the settlement, it is recommended to use the following expression of specific losses of flow:

$$q_{\text{leak}} = \left(Q_{\text{night}} - Q_{\text{cons.}}\right) / L_{\text{w}} \ (\ 1/\text{hour m})\ , \tag{1}$$

where

q_{leak} - specific loss of flow, l/s m,

Q_{night} - average night flow recorded by the zone flowmeter, l/h

$Q_{\text{cons.}}$ - the average consumption of subscribers during the night l/h,

L_{w} - length of pipelines of the zone, m.

In the sector of own residences, the accepted average consumption per subscriber during the night was 1.7 l/h, while in multi-apartment buildings, it was 0.6 l/h. These numbers are used to calculate the amount of leakage in the systems of European cities where operational circumstances match up with regional water supply systems.

Because customer overnight costs can significantly affect the zone's estimated night loss, they are calculated independently using actual data.

Results and Discussion

Analyzing the results of multi-year studies and considering the current technical situation of the distribution network, it is recommended to continue the accident detection and elimination work for the current phase until the night-time consumption of the zone is less than half of the daytime consumption:

$$Q_{night} \leq Q_{day}/2(l/s), \quad (2)$$

where Q_{night} and Q_{day} are the average water volumes given to the zone during the night (1^{00}-5^{00} period) and daytime.

The mentioned expression was defined after studying the zones with the lowest water losses in RA settlements (Davtashen, South West, and other districts). Thus, let's discuss the study results on the "Arabkir 1" zone, where the average amount of water supplied at night is 102 l/s, and during the day is 133 l/s. Applying the expression (2), we can determine the amount of leakage reduction in the “Arabkir 1” zone to meet the current stage requirements, which should not be greater than 133/2=66.5 l/s. From the data obtained, we can conclude that in the mentioned zone, there is still leakage of 102-66.5=35.5l/s more than the permissible one, which needs to be detected and eliminated.

Conclusion

To increase the efficiency of the aqueduct network, zoning problems were studied, taking into account the technical condition of the system. Scientific calculations were carried out, and a methodology for zoning was developed:

- The analyses showed that the water pipe network should be transformed into hydraulically separated zones while using the current distribution system, taking into consideration the position, placement, and dependence of the site's relief features. It was necessary to create a zone design and implementation that considers the principles of system management, the formation of sub-zones (dead-end networks), the calculation of optimal pressures, the detection and elimination of current losses, etc.
- To increase the level of management of zone distribution networks, the means of automatically transferring the fundamental characteristics of operation: pressure, output, and electricity consumption values are applied, the investment of which in water supply systems will give the desired results.

References

[1]. A.A. Sahakyan, Sectorization and Reconstruction Problems of Yerevan City's Water Supply Network. Bulletin of National University of Architecture and Construction of Armenia, 4 (48), 2015, 3-9 (in Armenian).

[2]. A.A. Sahakyan, Hydraulic Pressure Management of Yerevan City’s Water Supply Systems. Journal of Architectural and Engineering Research, 3, 2022, 78-84.
Doi: https://doi.org/10.54338/27382656-2022.3-009

[3]. K. Vairavamoorthy, J. Lumbers, Leakage Reduction in Water Distribution Systems: Optimal Valve Control. Journal of Hydraulic Engineering, 124(11), 1998, 1146-1154.
Doi: https://doi.org/10.1061/(ASCE)0733-9429(1998)124:11(1146)

[4]. L.S. Araujo, H. Ramos, S.T. Coelho, Pressure Control for Leakage Minimization in Water Distribution systems Management. Water Resources Management, 20, 2006, 133-149.
Doi: https://doi.org/10.1007/s11269-006-4635-3

[5]. M.Giugni, N.Fontana, D.Portolano, Energy Saving Policy In Water Distribution Networks. International Conference on Renewable Energies and Power Quality, Valencia, Spain, April 15-17, 2009.

[6]. S.Liberatore, G.M. Sechi, Location and Calibration of Valves in Water Distribution Networks Using a Scatter-Search Meta-heuristic Approach. Water Resources Management, 23, 2009, 1479–1495.
Doi: https://doi.org/10.1007/s11269-008-9337-6

[7]. N.Fontana, M.Giugni, D.Portolano, Losses Reduction and Energy Production in Water Distribution Networks. Journal of Water Resources Planning and Management, 138 (3), 2012, 237-244.

[8]. A.Di Nardo, M.Di Natale, A Heuristic Design Support Methodology Based on Graph Theory for District Metering of Water Supply Networks. Engineering Optimization, 43(2), 2011, 193-211.

[9]. S. Alvisi, M. Franchini, Una procedura per la distrettualizzazione delle reti di distribuzione idriche. In Proc. XXXIII Convegno Nazionale di Idraulica e Costruzioni Idrauliche, Brescia, Italy, 2012.

[10]. Francesco De Paola, Nicola Fontana, Enzo Galdiero, Maurizio Giugni, Gianluca Sorgenti degli Uberti, Marcello Vitaletti, Optimal Design of District Metered Areas in Water Distribution Networks. Procedia Engineering, 70, 2014, 449 - 457.

[11]. J. Sempewo, A. Pathirana, K.Vairavamoorthy, Spatial Analysis Tool for Development of Leakage Control Zones from the Analogy of Distributed Computing. Proceedings of the 10th Annual Water Distribution Systems Analysis Conference, Kruger National Park, South Africa, Aug. 17-20, 2008. Doi: https://doi.org/10.1061/41024(340)57

[12]. G.Karypis, V.Kumar, METIS: Unstructured graph partitioning and sparse matrix ordering system. Technical report, University of Minnesota, Department of Computer Science, 1995.

[13]. M. Herrera, J. Izquierdo, R. Pérez-García, I. Montalvo, Multi-Agent Adaptive Boosting on Semi-Supervised Water Supply Clusters. Advances in Engineering Software, 50, 2012, 131-136. Doi: https://doi.org/10.1016/j.advengsoft.2012.02.005

[14]. K. Diao, Y. Zhou, W. Rauch, Automated Creation of District Metered Area Boundaries in Water Distribution Systems. Journal of Water Resources Planning and Management, 139 (2), 2013, 184-190. Doi: https://doi.org/10.1061/(ASCE)WR.1943-5452.0000247

[15]. R.Gomes, A.Sa Marques, J. Sousa, Decision Support System to Divide a Large Network into Suitabledistrict Metered Areas. Water Science & Technology, 65(9), 2012, 1667-1675. Doi: https://doi.org/10.2166/wst.2012.061

[16]. F.A. Shevelev, A.F.Shevelev, Tablitsy dlya gidravlicheskogo raschota vodoprovodnykh trub. Stroyizdat, Moscow, 1984 (in Russian).

[17]. A. Sahakyan, Water Loss Assessment in the Internal Water Supply Networks of Yerevan City Apartment Buildings and Private Houses. Scientific Papers of National University of Architecture and Construction of Armenia, 85 (1), 2023, 132-143. Doi: https://doi.org/10.54338/18294200-2023.1-14

***Aram Sahakyan, Doctor of Philosoph (Ph.D) in Engineering** (RA, Yerevan) - National University of Architecture and Construction of Armenia, Dean of the Construction Faculty, sahakyan.aram@nuaca.am*