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WATER RESOURCES PROTECTION BY CONTROLLING WATER SUPPLY NETWORK LEAKAGES

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Abstract

Deficiencies in the availability of water resources are a barrier to urban development. Due to the progressive climate changes, water stress occurs not only in arid and semi-arid areas, but also in some regions of Central Europe. As rivers are common water sources for water supply systems, in many locations the amount of water taken in began threatening the biological life in rivers. The protection of these sources has now entered a new phase – it is not only required to preserve the adequate quality of water, but also its quantity. One of the first steps in protecting water sources involves increasing the efficiency of water usage in water supply systems. Firstly, the efficiency of water use can be increased by limiting the water losses from a water distribution network (WDN). It is a complex task, which should be solved shortly after its occurrence. A proper detection system is key to successfully limiting the water losses. The aim of this paper was to present a case study of the exemplary leakages detection by the application of such advanced tool. As it was proven, even partial reduction of water leakages from WDN can result in the protection of local water resources.

***Keywords**: Protection of water resources; Water supply systems; Leakage; Monitoring*

Introduction

Water supply systems are part of the critical infrastructure systems, which guarantee the life safety and comfort of the citizens [1]. The most important element of these systems are water sources, the availability of which determines the water supply functioning. The water resources should be significantly higher than the water demand. Unfortunately, especially in arid and semi-arid areas, the demand for water often equals or even exceeds the available amount of water during a certain period. This situation is called the water stress. In such case, the population and economy development barrier is reached [2]. The progressive climate changes caused that the high level of water stress periodically occurs even in the Central European area, the region which has not experienced the water scarcity problem thus far [3]. The lowering of water stress can be achieved in two main ways: by increasing the amount of available water (e.g. by new water sources) or by limiting the water use. The fastest possible method in the second way of lowering the water stress is minimization of water leakage from water distribution networks (WDN). Limiting of water losses is especially important in the cases where there is also a problem of exceeding the safe amounts of water taken in form the biological point of view. The level of water losses differs significantly depending on the location. The exemplary percentage data levels of water losses in large cities in different parts of the world are presented in Table 1 [4]. Depending on the location, water losses in large cities vary significantly, from 6÷14% in Western Europe, up to 42% in Africa and Latin America.

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However, it is worth mentioning that the water losses situation in small cities is usually worse, due to the limits in founding of operational services, lack of diagnostics tools and uncommon rehabilitations of pipelines. Hence, in the case of reducing the water losses, there are significant water reserves for the demand purposes. Moreover, the leakage reduction can also decrease the water stress level, and in further perspective, help to restore the water resources.

Table 1. Percentage levels of water losses in large cities in different parts of the world [4]

Large cities in	%
Africa	42
Latin America	42
North America	10÷25
Asia	39
Western Europe	6÷14
Eastern Europe	12÷40

The water losses in water distribution systems (WDS) are caused mainly by pipe breakages and valves failures. Pipe breakages are an inherent part of the operation of every water distribution system [5]. Due to their random character, it is impossible to predict the future location of a pipe failure [6]. As a result of pipe breakage, in addition to its main consequence which is the limitation of a water delivery to customers, the most onerous issue is water loss. Nowadays, especially in the drought-stricken areas, it is important to locate and repair breakages quickly in order to save water. Unfortunately, not all leakages are easy to notice. While burst leakages are relatively simple to locate as their effects usually can be easily observed (e.g. suffusion holes, lack of water delivery, water outflow to the soil surface), the background leakages can remain unnoticed for a long time [7]. However, if a leakage generates a sufficient pressure drop or flow increase, even hard-to-detect background leakages can be visible in the online monitoring system.

Generally, there are two main ways to detect pipe breakages: using hardware and software. While the application of the hardware methods (geophones, noise correlators, ground-penetrating radars, etc.) is usually highly effective, it is also time consuming and therefore, their application in real-time leakages detection is quite difficult [8]. On the other hand, the software methods (e.g. Minimum Night Flow method (MNF), Negative Pressure Wave method (NPW), transient wave [9,10] are indirect ways to detect leaking pipe, but they are analogically impossible to use in the on-line diagnostics, since it requires prolonged data collection. The example of cooperation of both the hardware and software detection method is the hydraulic modelling, Supervisory Control and Data Acquisition (SCADA) systems and hardware tools application. On the basis of the SCADA data, the software restricts the possible water leakage area and then the damaged pipe can be precisely detected e.g. by geophones. The necessary requirement for successful leakage detection in the approach is the proper division of the WDS into monitoring zones (District Metered Areas (DMAs)).

The continuous monitoring of flows into and out of the controlled zone is now the internationally accepted approach of active leakage control. It requires the installation of flow meters at representative points in the WDS [11]. Each DMA should be restricted by permanently closed boundary valves or boundary elements (e.g. tank, pressure reducing valve (PRV), pump, isolation valves). Ideally, the DMA should be supplied with one inflow, but sometimes two or more inflows are accepted [12]. The DMA size can vary, but it is recommended that it should cover between 500 and 3000 house connections. The concept of DMA management is to continuously monitor the flow into the DMA and analyse the night flow in order to find possible excesses over the customer use. Unfortunately, the water audits over DMAs provide only the information about the approximate area having excessive leakage. Therefore, hardware detection is required to pinpoint the leak [13].

The aim of this paper was to present a case study of water resources periodically exceeding the safe biological level in a river – the only water source for the water supply system, which supplies the whole city. As a solution to this problem, the authors proposed increasing the water efficiency usage by applying an integrated method of detection and localization of water leakages. The goal of the paper was to prove that even a partial reduction of leakages can contribute to the water resources protection of the water supply source.

Materials and Methods

The presented case study concerns a city located in a mountainous area in Poland. The only water source for this city is a river, the discharge of which is highly dependent on the snow cover and precipitation. The average river volumetric flow, used for the design purposes, is $0.62m^3/s$ ($53\ 568m^3/d$). The minimum environmental flow, considered sufficient for protecting biological life, the function and structure of an ecosystem and its dependent species, equals to $0.32m^3/s$ ($27\ 648m^3/d$). The available water resources equal to $0.3m^3/s$ ($25\ 920m^3/d$). In July 2019, after an almost snowless winter and two-month drought, the discharge decreased to $0.40m^3/s$, limiting the available water resources to $6\ 912m^3/d$. At the same time, the demand for water increased to $7\ 080m^3/d$. The water delivery through WDN resulted in exceeding the environmental flow of the river. The case of protecting water sources surprised the local authorities and became a priority.

The analysed WDS is very complex and consists of 24 pressure zones, with several pumping stations and tanks. WDS delivers water to approx. 30 000 inhabitants. Among the typical household customers, in the analysed WDS, there are several industrial customers, demanding water in significant amounts at a random time of day. The prevalent pipe material is PVC and PE, but the oldest parts of the network consist of asbestos cement, ductile iron and steel pipes, mainly in the old-town district. Total pipe length equals to approx. 260km and the total daily water demand is approx. $3\ 850m^3/day$ ($128.3dm^3/(d\cdot person)$). However, the demand of water can periodically increase to $7\ 120m^3/day$ ($237.3dm^3/(d\cdot person)$). The analysed WDS is characterised by great water losses, varying from 7% up to 43% between zones. In the majority of 24 pressure zones, the population density can be described as low or medium, which usually results in long breakage detection time – the water outflow to the surface can be noticed in a few to several days. The geometrical structure of the analysed WDS, with elevation contours and size-scaled diameters is presented in figure 1.

Because of the necessity of protecting the water resources, the water company initiated a water losses reduction plan, as a part of a general project of WDS managing, under which the hydraulic model of a WDS was developed. The model of a basic character (including all pipes excluding household connections, total length: approx. 221km) was created in Bentley WaterGEMS software, consisting of approx. 11 000 pipes and junctions. The extended period simulation (EPS) model was developed in accordance to the GIS database, with calculation time step equal to 20 minutes and total duration of 168 hours (7 days). The obtained compliance of a calibration process is $\pm 1.5m\ H_2O$ in 55 pressure calibration nodes and $\pm 10\%$ of water flow value in 45 calibration pipes. The calibrated model was further connected with the existing SCADA system, in order to constantly compare the calculated and measured water pressure and flow values, at every time step of the simulation. On the basis of the created application, supporting the WDS operator, the appropriate alarm levels were established for all monitoring points. Whenever the alarm level is exceeded, the adequate notification is displayed on the user’s panel. The acceptable pressure exceedance was specified as $\pm 5m\ H_2O$ and the acceptable flow limit exceedance was $\pm 18m^3/h$. If the alarm notification cannot be identified with a known reason (open hydrant, purposely closed valve, etc.), the possible leakage area can be restricted using the hydraulic modelling. In order to locate the leakage, the Darwin Calibrator of the Bentley WaterGEMS software was used.

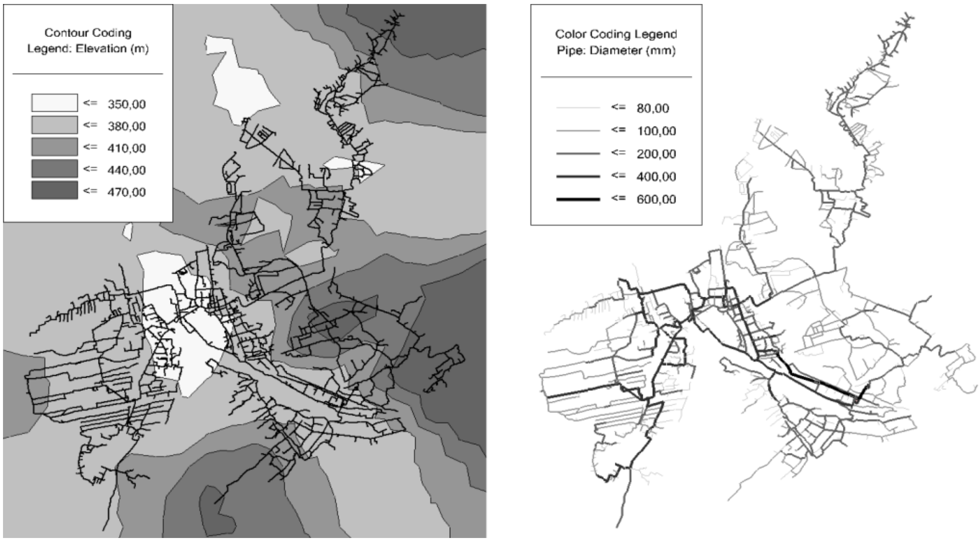

Fig. 1. Geometrical structure of the WDS with elevation contours and pipe diameters

The Darwin Calibrator uses a genetic algorithm (GA) not only to support the calibration process but also for leakage detection and identification of closed valves in a water supply system. The general idea of Darwin Calibrator is to compare the measured and calculated values of the same parameter and search for the most appropriate solution based on the principles of natural evolution and genetic reproduction [13]. The results of leakage detection are presented in the colour coding form. The leakage is figuratively presented as emitter coefficient, which are most often used to model irrigation and sprinkles systems, but can be also successfully used to simulate the pressure dependent pipe leakages or fire flows at hydrants [14]. The emitter flow varies as a function of a pressure available at the associated node, in accordance to the formula (1) [15, 16].

$$q = C \cdot p^n \qquad (1)$$

where:
q – flow rate (dm^3/s),
C – emitter coefficient ($dm^3/s\ m^n$),
p – pressure head (m H_2O),
n – pressure exponent (0.5).

In the presented case study, 5 different zones (presented in figure 2) were selected in terms of the presence of monitoring points in a zone. The selected zones included:

I DMA with pressure and flow measuring devices only at pump station (total pipe length in a zone: 856m),
II DMA determined by pressure reducing valve (PRV) and one network water pressure monitoring tool (total pipe length: 1 560m),
III DMA with pressure and flow measuring devices at pump station and one network water pressure monitoring tool (total pipe length: 2 217m),
IV DMA with pressure and flow measuring devices at pump station, one network flow meter and one network pressure monitoring tool (total pipe length: 14 143m),
V A complex transmission zone equipped with 12 pressure and 8 flow monitoring tools (total pipe length: 47 319m).

The exemplary leakage detections were conducted on the basis of fire hydrant tests. In every selected zone (different DMAs), the random fire hydrant was opened for 5 minutes, causing significant water outflow (zone I – outflow 21.1m^3/h, II – 43.8m^3/h, III – 22.2m^3/h, IV – 57.1m^3/h, V – 49.5m^3/h) and therefore the water pressure drop. In all cases, the hydrant outflow exceeded the acceptable flow variation limit (±18m^3/h) and hence the flow alarms should be noticed in the zones with flow meters. In the first step of the leakage detection, the monitoring system was checked whether the alarm responses were adequate. Secondly, the Darwin Calibrator module was used for each case to identify the potential leaking node.

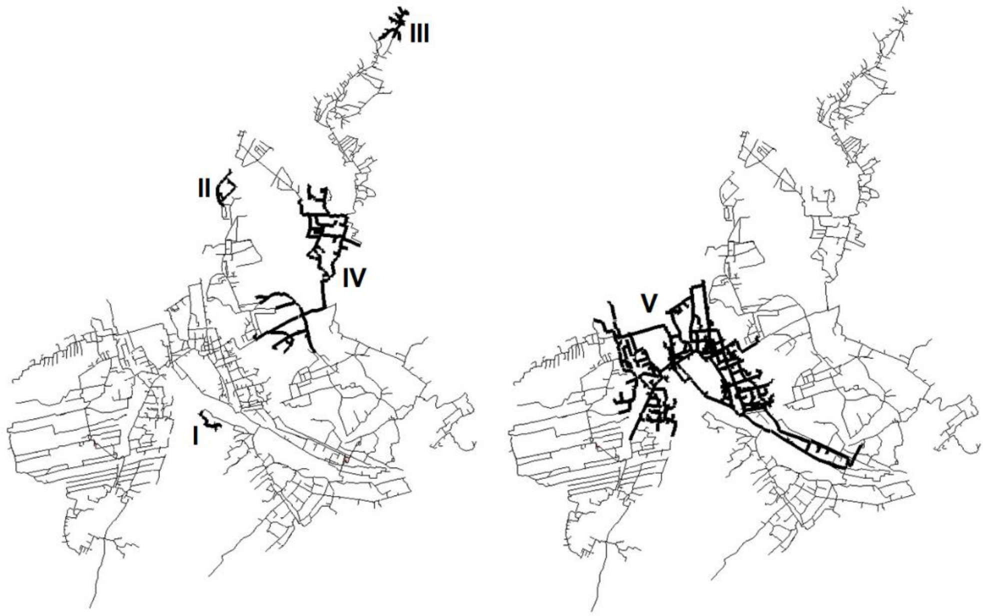

Fig. 2. Geometrical structure of WDS with the analysed zones marked in bold (zone I-IV and V)

Due to the fact that Darwin Calibrator is very sensitive to the data of poor quality, the SCADA raw data were firstly carefully verified. If the data, which supply the genetic algorithm implemented in Darwin Calibrator is inaccurate, the pointed leaking node can be located far away from the actual leakage location. In the analysed case, the leakage detection system was tested for the leakages artificially caused by fire hydrant openings during the hydrant head loss roughness tests. It turned out to be a major difficulty because the hydrants selected for the roughness tests were usually located at the edges of zones, away from the measuring points. Of course, such dead-end locations are theoretically possible locations of pipe failures; however, the presented leakage detection system can only be applied if the water outflow can raise the alarm at the operator display. Further, the leakage detection process was continued with the use of Darwin Calibrator module of Bentley WaterGEMS software. After the verification, appropriate data were imported into the module. Each zone was analysed separately as a New Leakage Study. All demands within the zone were classified as a common demand adjustment group. The minimum and maximum emitter coefficient was established as 0 and $20dm^3/s/(m\ H_2O)^n$, with the increment equal to 0.01. In each case, maximum 5 potential leaking nodes were searched for. The leakage detection was performed for the defaults genetic algorithm settings: fitness tolerance: 0.001, maximum trials: 10 000, non-improvement generations: 100, maximum era number: 6, era generation number: 150, population size: 50, cut probability: 2%, splice probability: 90%, mutation probability: 1.0%, random seed: 0.5. The results were further compared with the known location of the open fire hydrants and considered as successful if the distance between pin-pointed leaking node and open fire hydrant was no greater than 150m. The results are presented in two parts: firstly zones I-IV and next zone V.

Results and discussion

The presented method of water resources protection by increasing the efficiency of water usage (limiting its losses) was tested by the analysis of the potential alarms triggered by open fire hydrants. The pressure graphs in zones I-IV are presented in figure 3. In zone I, the pressure drop response was checked at the pumping station, in zones II and III at the network pressure monitoring points and in zone IV at the closest located pressure monitoring point. In all four cases, the pressure changes exceeded the accepted variation limit ±5m H2O and therefore the WDS operator should be alarmed about the unusual pressure drop. The visible two pressure drops in zone I mean the opening, closing and reopening of the same hydrant during the test, because of some technical issues.

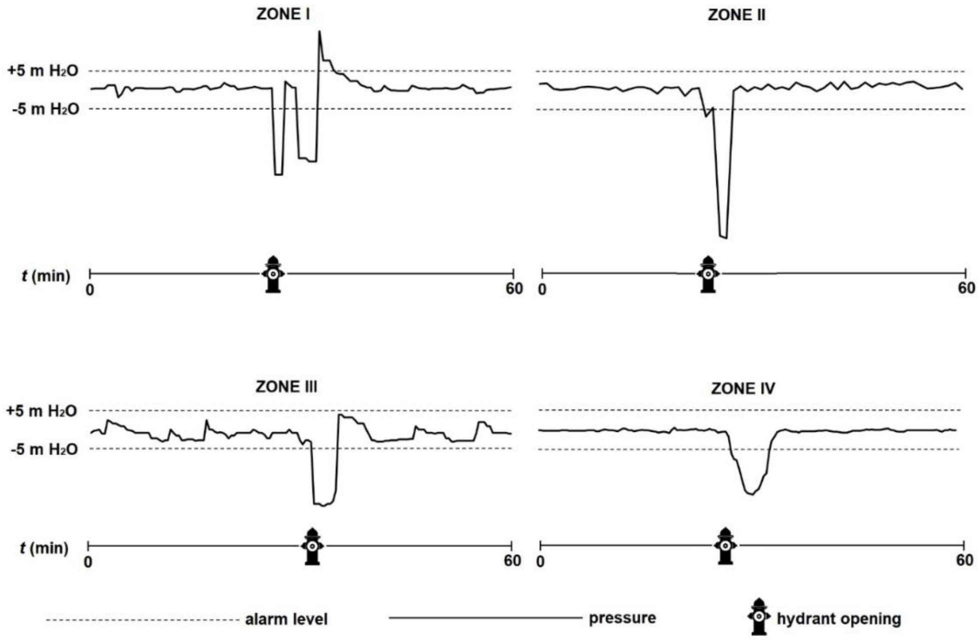

Fig. 3. SCADA indications (pressure) at monitoring points during the fire hydrant opening in zones I-IV – pressure alarm levels exceeded

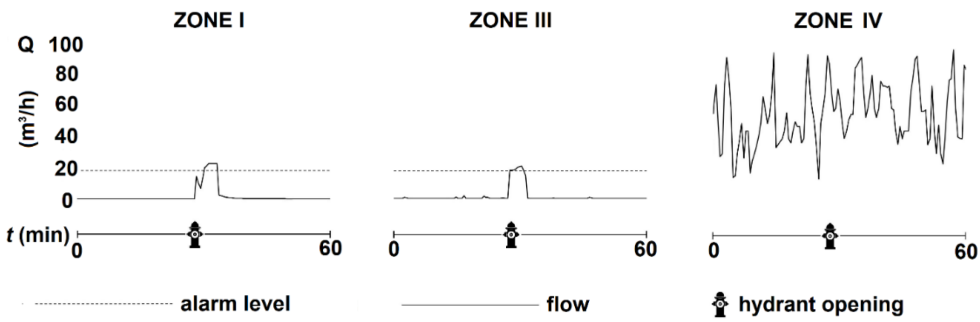

Fig. 4. SCADA indications (flow) at monitoring points during the fire hydrant opening in zones I, III & IV – flow alarm levels exceeded in zones I and III

In addition, in zones I, III and IV the flow increase was checked at the monitoring points (in zones I and III, the flow meters were located in water pumping stations, in zone IV – a network flow meter). The flow graphs in zones I, III, IV are presented in figure 4. In two out of three cases, the hydrant opening induced a visible flow increase at the monitoring points (alarm levels exceeded). In zones I and III (end zones of the WDS), the usual water flow is relatively small (0÷1.5m^3/h) and therefore the hydrant opening and water outflow (respectively 21.1 and 22.2m^3/h in zone I and III) caused a clearly visible flow peak. On the other hand, in zone IV, where the flow was metered in the centre of the zone, the normal flow varies from 20 up to

100m^3/h. The WDS operator, even when alerted by the alarm, would not be able to associate the flow raise with the leakage (hydrant opening) because the flow increase is in the range of the normal flow variations at this monitoring point. Therefore, in that case, the leakage detection was mainly based on the observed pressure drop.

The main purpose of the presented detection system was to limit the area of possible leakage location. The potential leakage locations are visualised by grey scale colour-coding on the network graph by setting a suitable emitter coefficient for WDS nodes in figure 5. The water company operating the analysed WDS requested that leakages should be located with the accuracy of 150m. The calculated leaking nodes were in the distance of an actual leaking location (open fire hydrants) at 1.0, 87.5, 33.0 and 277.0 meters for zones I-IV, respectively. The locations of 3 out of 4 leakages were successfully found in the acceptable distance specified by the water company (150m). At the smallest zone I (0.39% of the WDS pipe total length), the leakage was detected precisely at the open hydrant. In contrast, in semi-large zone IV (6.4% of the WDS pipe total length), the leaking node was 277.0m away from the open fire hydrant. This unsatisfactory accuracy of the leakage location in zone IV is estimated to be caused by the unhelpful recordings of the network flow meter and the size of the zone. However, considering both size and transition character of the zone, the detection accuracy can be considered relatively satisfactory.

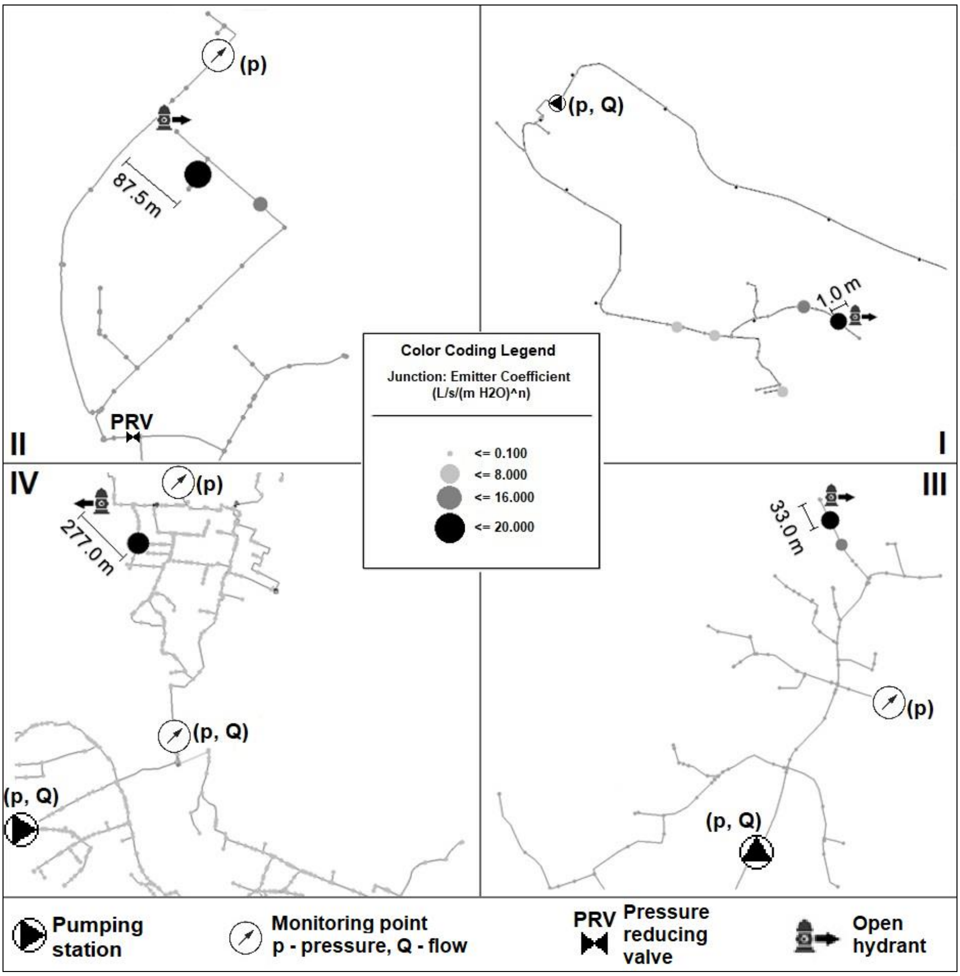

Fig. 5. Water leakage detection results in zones I-IV

On the contrary to the successful results, there is an example of the leakage detection failure in zone V. Zone V is the largest zone of the analysed WDS (21.41% of the WDS pipe total length) and supplies all surrounding zones with water as the only water intake in the WDS is located in this zone. Zone V is also the oldest zone in the WDS (over 50 years of operation), consisting mainly of asbestos-cement, steel and ductile iron pipes. As a consequence, the greatest water losses in the WDS are recorded in this zone (43%). The open fire hydrant in zone V was located quite far from the monitoring points – the closest located pressure monitoring point was located at a distance of 290m from the open hydrant. The geometrical structure of the zone V and SCADA indications at the closest located pressure monitoring point during the opening of the fire hydrant are presented in figure 6.

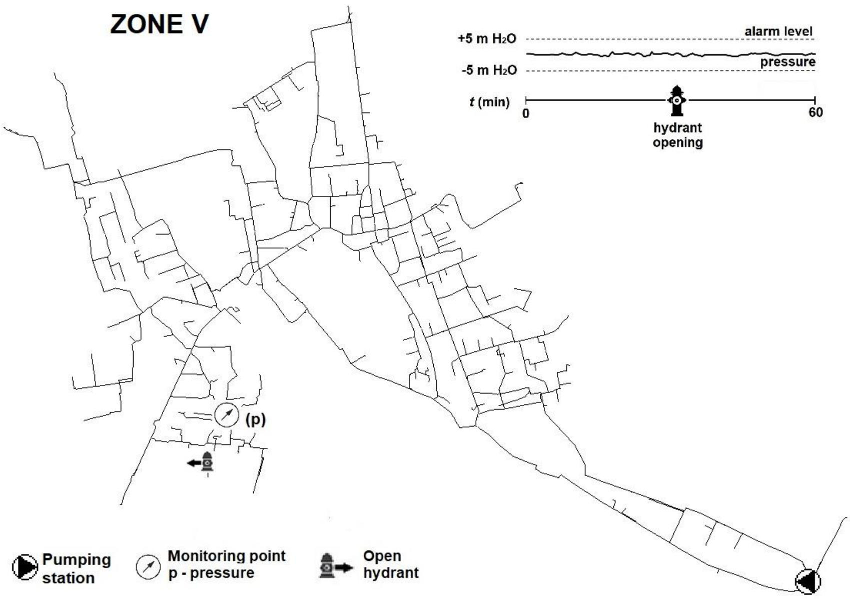

Fig. 6. Geometrical structure of the zone V and SCADA indications at the closest located pressure monitoring point

The hydrant opening caused the pressure decrease from 24.12m H_2O to 22.21m H_2O, which means that the pressure variations are within the acceptable tolerance level (±5m H_2O). In such case, the alarm level was not exceeded. Lowering the alarm level was considered at this point. Unfortunately, it was not possible, as the normal pressure at this monitoring point varies ±2m H_2O and the opening of the hydrant is causing only a slight pressure drop (1.91m H_2O). Despite the unsatisfactory SCADA indications at the closest monitoring point, the other existing points were verified as well. Zone V is equipped with 12 pressure and 8 flow monitoring devices. Unfortunately, none of the devices recorded the pressure or flow changes that would alarm the operator. Even the significant hydrant outflow (49.5m^3/h) fall within the range of normal flow changes at the flow monitoring points. Despite the fact that the alarms were not triggered, the leakage detection procedure was continued but the results were completely wrong and meaningless for all approaches (with different GA settings). As a result, it can be said that the zone V, due to its size and transition character, is not sensitive enough for the hydraulic modelling leakage detection. As the analysis in zone V proved, the key role in a successful detection and location of the leakages is the significant quantity of metering devices and proper division of the water distribution system into district metered areas.

Considering the obtained results, the water company decided to implement the advised leakage detection approach in zone V, including dividing zone into DMAs and equipping with new metering devices. The system started operating at the turn of February and March 2020. The implementation of approach integrating different ways of detecting and locating water leakages resulted in a noticeable decrease in water losses in the analysed WDS – presented in figure 7. What is worth mentioning, is that no other methods of decreasing water leakages (renovations or rehabilitations of pipelines) were applied in the analysed period. The water loses in the analysed system decreased by 4.8% which equals to 184.8m^3/d of the demanded water by a total of 1 440 customers. The water losses reduction decreased the total water demand from 7 080 to 6 895.2m^3/d. which is lower than the minimum available amount of water resources recorded in July 2019 (6 912m^3/d).

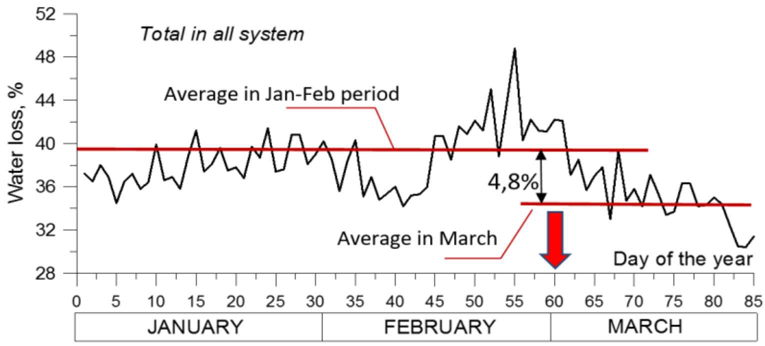

Fig. 7. Water losses decrease in 2020 as the effect of dividing zone V into DMAs (red arrow – the start of the leakage reduce system operation)

Therefore, the application of the analysed leakages detection even in a single zone enabled to protect the water source and ensure the environmental flow in the river the water source for the water supply system. However, it should be underlined that the presented water losses reduction did not allow decreasing the water stress significantly in the analysed WDS. Therefore, the further urban development of the city requires the implementation of the complete leakage detection system in all zones of the WDN, but also undertaking other preventive actions, such as finding alternative water sources.

Conclusions

Due to the progressive climate changes, water stress occurs not only in arid and semi-arid areas, but also in some regions of Central Europe. This phenomenon surprised the local authorities and enforced the implementation of remediation methods. One of the methods involves increasing the water efficiency usage by limiting its losses. It can be accomplished with the method of detecting and locating water leakages described in the paper. The presented method was implemented for a couple of autumn months in one of the 24 zones of the analysed WDS. Even such extemporary action resulted in protecting the environmental flow of the only local water source.

The application of the complete system in all zones, together with undertaking some preventing actions, should significantly lower the periodically occurring water stress in the analyzed region. It should also give time and the possibility to search for the alternative water sources. Otherwise, the environment protection, further urban and economy development of the city are going to be severely hindered.

The presented method of limiting water losses by detection and location of water leakages can by implemented in other water supply systems, which can successfully contribute to the protection of water resources of the regions exposed to water stress. However, the application of the method has to be each time combined with an insightful analysis of the geometrical structure of the water supply network as well as defining the required amount and location of monitoring sensors.

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