ORIGINAL ARTICLE

Smart water supply system: a quasi intelligent diagnostic method for a distribution network

Dariusz Kowalski[1] · Beata Kowalska[1] · Paweł Suchorab[1]

Abstract

Constantly developing monitoring systems provide a large amount of raw data. In many cases, the operators of water supply systems (WSS) have already reached their perception limit for analysing information. Therefore, the managing process of the WSS requires quasi-intelligent informatics systems, the main purpose of which is to minimise the WSS operating costs in addition to maintaining the proper water delivery to customers. It can be achieved by the detection of abnormal functioning of WSS operations (leakages, water outages). The standard SCADA monitoring systems, in most cases, are not able to distinguish a significant water leakage and water tank filling process. Such cases occur relatively often in complex water supply systems with many water tanks. The aim of this paper is to present the quasi intelligent method of detecting abnormal WSS functioning, including its concepts and effects after a 3 month period operation. The essence of the detection method is the integration of numerical model (built-in Bentley WaterGEMS software) and SCADA monitoring system. The monitoring data are constantly compared to the simulation results and when accepted accordance limits are exceeded, the appropriate alerts are generated. Such solution cause the WSS operator does not need to analyse SCADA system indications constantly. The additional application of the method enables the detection of essential water leakages.

Keywords Water network · Diagnostic method · Water losses · Leakages

Introduction

The main goal of water companies in the supply of recipients with water. The delivered water has to be provided in adequate amounts and under appropriate pressure. It also has to be safe for consumption (Council Directive 1998). In order to operate effectively, water supply companies need to be economically efficient. This necessitates limiting the energy costs, reducing the water losses, as well as improving the reliability of the water supply systems (Lenzi et al. 2013; Shirzad and Tabesh 2016). These requirements enforce constant development of monitoring systems. Monitoring encompasses, among others, the hydraulic conditions of water supply system operation, the quality of transmitted water, as well as energy consumption (Carrico et al. 2014; Stańczyk and Burszta-Adamiak 2019).

The number of installed sensors related to monitoring, and simultaneously the amount of recorded data, are on a constant increase. In many cases, the operators of water supply systems (WSS) have already reached their perception limit for analysing information. Thus, water supply companies are forced to provide new tools which help operators in decision-making process. These tools have subsequently been transformed into smart water systems. This term denotes the integration of a set of products and informatics algorithms that enable to remotely utilitise as well as continuously monitor and diagnose problems, prioritise and manage maintenance issues and use data to optimise all aspects of the water distribution network (Savic 2015). There are numerous other definitions of such systems (Tao et al. 2016; Lee et al. 2015). However, all of them emphasise the key role of diagnostics of water supply systems and informing the operators about emergencies. Realisation of these tasks requires integration of a monitoring system, analysis of the collected measurement data as well as informatics tools identifying emergency states (Albino et al. 2015; Allen et al. 2012). The first group of the above-mentioned tasks is already commonly realised by means of SCADA

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(Supervisory Control And Data Acquisition) systems. However, tools for automatic identification of emergency states are rarely implemented in water supply companies. There are no standards for identification of such states or the necessary software. Diagnostic methods are usually implemented in stages, depending on the financial abilities of the water supply companies. Most often, the leakage detection methods are implemented first. Nevertheless, new methods of such detection are still being sought (El Zahab and Zayed 2019). The aim of the paper is the presentation of a novel quasi-intelligent diagnostic method, integrating SCADA system and numerical model of the water supply system. In assumptions, an informatics tool built on the basis of this method is to detect abnormal operation of the water supply system, such as large water leaks or incorrect operation of the pumping stations. It was implemented in an existing multi-zone water supply system. The paper presents the effects of their implementation, corresponding to the first three months of operation. The method's advantages, as well as identified limitation, necessary amendments, and further development ideas, were also presented.

Materials and methods

Description of a water supply system

The quasi intelligent diagnostic method presented in the paper was implemented in an existing water supply system of a city with approximately 30,000 inhabitants, located in a mountainous region. Apart from the historical city centre, the population density is low. This leads to the situation where a water leakage remains undetected for several days. The analyzed water supply system is supplied from a single surface water intake. On average, 7500 m^3 of water is pumped into the system per day. The seasonal variability of the amount of pumped water is presented in Fig. 1. The difference between the maximum and minimum volume of water pumped into the system each year, compared to the

average for 2005–2019, calculated using formula (1), was 24%. Similarly, taking into account the monthly mean values presented in Fig. 1 (right), the difference amounted to 17%.

$$n = \frac{Q_{\max} - Q_{\min}}{Q_{\mathrm{aver}}} \times 100\% \tag{1}$$

The total length of water supply pipes without house connections amounts to 260 km. Due to the significant differences in elevation of particular areas of the city, exceeding 150 m, the water supply system was divided into 24 pressure zones. This was connected with the need of installing 7 network tanks and 15 zone pumping stations. All network tanks are located at the inlet of the designated water supply zones. Despite the implemented zone division, the pressure value exceeds 120 m H$_2$O in some pipes of the network. The network was constructed using cast iron, steel, PVC, PEHD, and asbestos-cement pipes. The oldest, over 40 years, cast iron pipes constitute approximately 33% of network length. The scheme of the network along with the location of pumping stations and network tanks was presented in Fig. 2.

Due to the unsatisfactory technical condition of the oldest pipes and locally high pressure, the level of water losses in the analysed water supply system is high and approximates 38%. Before the implementation of the proposed diagnostic method the local water supply company was not aware of the spatial distribution of the losses. This was connected with the:

- Water meter reading schedule (once per 2 months),
- Transit function of 6 out of 24 zones,
- Functioning of the periodically filled network tanks,
- Lack of adequate number of flowmeters and network manometers.

Taking these factors into account, the company had no means of detecting large malfunctions, having to rely on the feedback of network recipients. This situation led to the
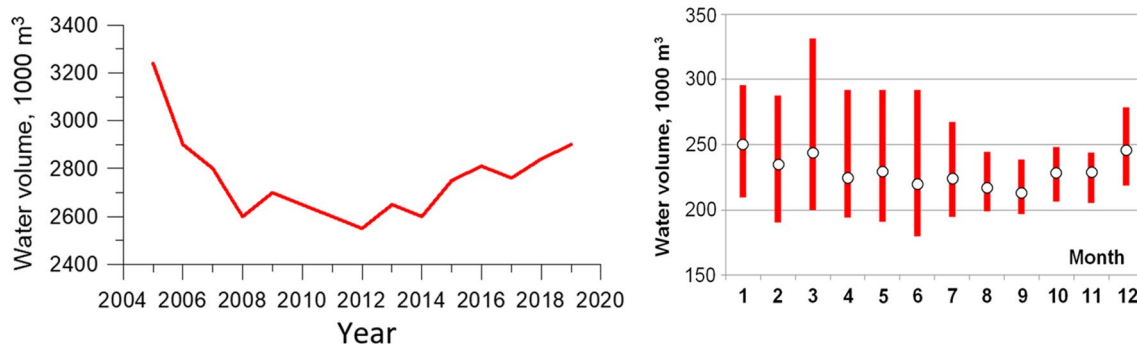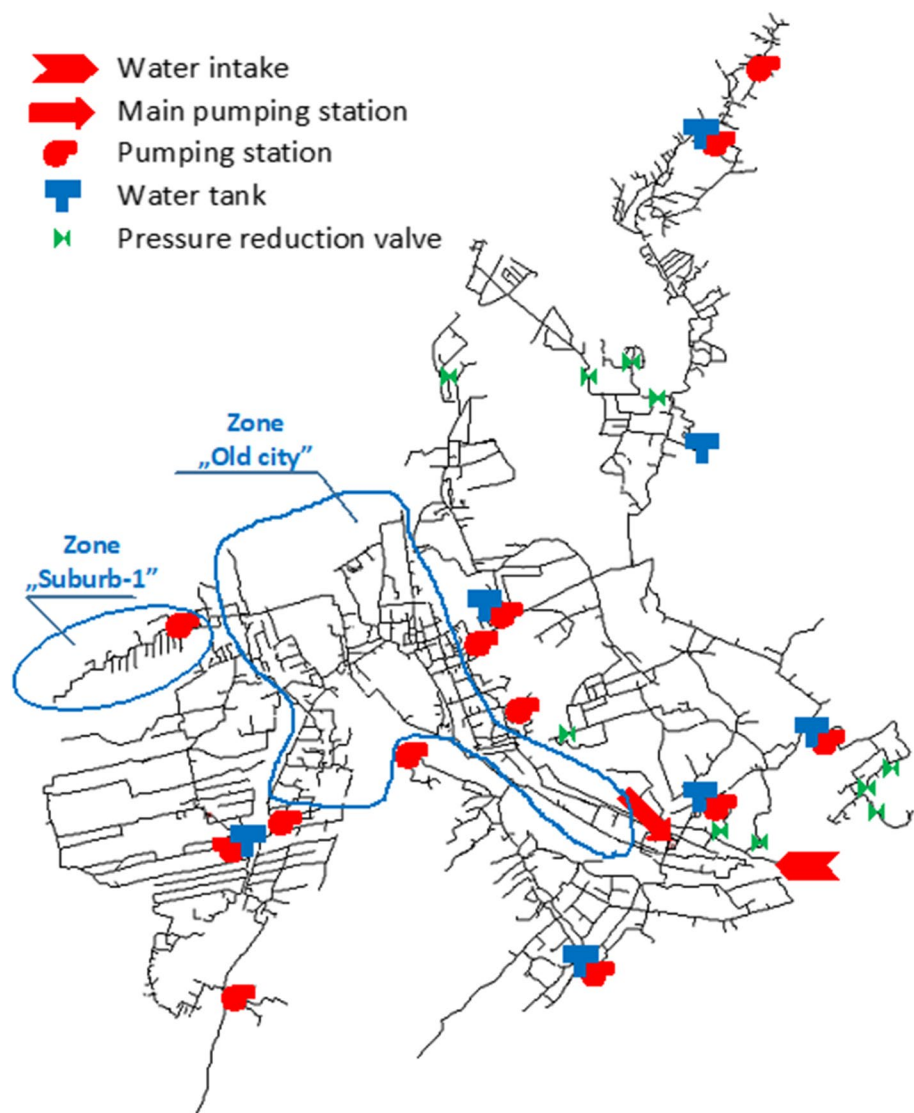

Fig. 1 Volume of water pumped into the water supply system yearly (left) and monthly minimum, maximum, average (right) in 2005–2019

Fig. 2 Scheme of the geometrical structure of a water supply system with the location of the intake, pumping station, and network tanks

implementation of a method which would enable a rapid diagnostic of emergency states.

While solving these problems, the water supply company decided to expand the monitoring system. In the beginning, a remote water meter reading system was implemented. This system enables direct transmission of data from water meters to the dispatching centre, using GSM network. Readings can be performed in programmable time-steps (from 5 min to 30 days). Additionally, the number of sensors in the network was increased. The current pressure and flow measurements are carried out using 58 manometers (38 at input points of each zones) and 47 flowmeters (38 at input points of each zones). The greater number of sensors than the number of zones is due to the necessity to measure the input and output from network tanks. The authors of the paper had no influence on the location of these points. The monitoring system expanded by the water supply company also involves measuring the filling level of all water network

tanks. The measurement devices were integrated into the SCADA system.

The next step realised by the company consisted in building a GIS database comprising all the objects and devices of the analysed water supply system. Additionally, the database includes the readings of water meters and ensures electronic circulation of documents within the company. The created database operates according to the standard proposed by ESRI.

Following the launch of the complex monitoring system, a problem with the interpretation of collected results from network sensors occurred. Dispatchers were unable to identify the emergency states of the water supply system operation, especially in the situation where constant significant water loss was observed. The number of measurement sensors turned out to be excessive for the perception of a single person. It was necessary to develop a specialized method and informatics tools using it, which would be based on the

solutions already implemented in the company and would facilitate the work of dispatchers. Both the method and the tool are presented in this paper.

Description of the diagnostic method

The essence of the detection method is the integration of numerical model (built-in Bentley WaterGEMS software) and SCADA monitoring system. The parameter values read by the monitoring sensors are compared with the results of computer simulations. Exceeding the permissible difference between them generates an alarm warning the dispatcher about the occurrence of abnormal operation of the water supply system. The implementation of the method required the development of an appropriate informatics tool.

The concept of a proposed diagnostic method devised by the authors had to account for the limited financial abilities of the company. Therefore, the proposed method has to be treated as under development and possible to update in the future. It was launched at the beginning of 2020. The system is still in the testing and adjustment phase. The GIS database created beforehand, which integrates the SCADA system and remote water meter readings, was adopted as the basis of the method. Two additional layers describing base demand and the status (open/close) of the network valves were created. Moreover, a numerical model of the investigated water supply system was connected to the database. The schematic diagram of the elaborated informatics tool was presented in Fig. 3. In the current configuration, the proposed method was aimed at the realisation of two tasks: assessment of water loss as well as detection and localisation of leakages. The GIS database constitutes a centre which integrates all actions. Integration was achieved by assigning identical addresses of particular objects, water meters, and monitoring sensors in all modules. This facilitates the transmission or access to the data in the database for particular modules.

The first task of the method is an assessment of water loss basing on the balance of the readings from the flowmeters supplying particular network zones, with the sum of the water meters readings of all recipients assigned to that zone. The time-step of balancing is connected with the programmed reading frequency and can range from 5 min to 30 days. Taking into account the lifespan of the batteries, a daily time-step of readings was set. The water losses correspond to a difference between the volume of pumped water and the water received by the recipients in a given zone. This is a simple task in the case of District Meter Areas (DMAs). Its complexity is greater in the case of locations in a given zone of a network tank and when dealing with a transit zone, transmitting water to other zones. Therefore, the water losses were based on the following equations:

for DMA zones

$$Q_L = Q_{IN} - Q_T - Q_{WM} \tag{2}$$

for transit zones

$$Q_L = Q_{IN} - Q_T - Q_{TRAN} - Q_{WM} \tag{3}$$

where Q_L volume of lost water, Q_{IN} volume of pumped water, Q_T volume of water used for technological purposes, Q_{WM} volume of water registered by recipients' water meters, Q_{TRAN} volume of water transmitted to other zones.

Equipping all tanks with the water meters recording the influent and effluent water enabled to greatly simplify the balance calculations. The filling of a tank is calculated as the volume of water transmitted to a zone which begins with a

Fig. 3 Schematic diagram of the proposed diagnostics method
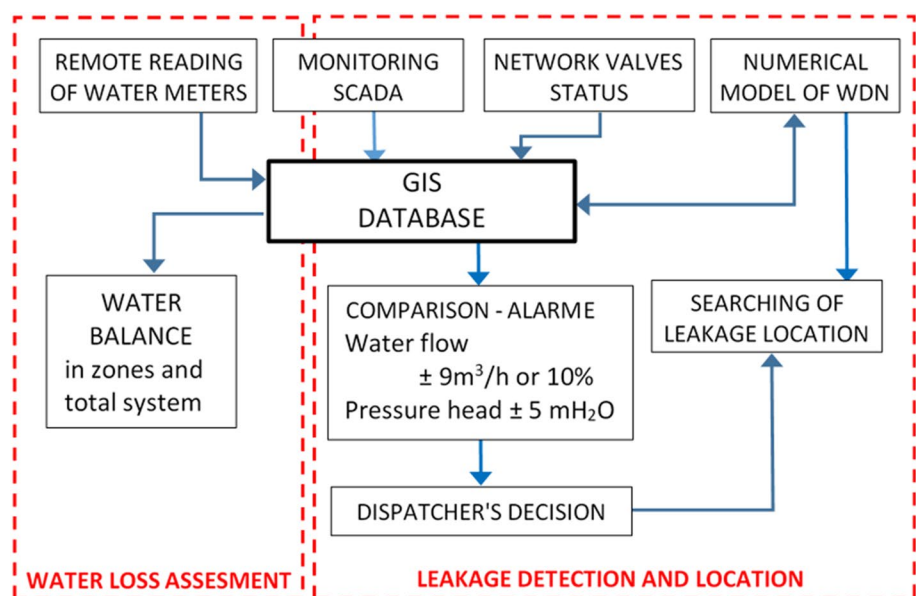
tank. Discharge from a tank simultaneously corresponds to the volume pumped into that zone.

The employed algorithm for assessing the water losses enables not only to determine the volume of water lost in particular zones but also evaluation expressed as percentage in relation to the volume of water pumped into a given zone (δ_{Zone}) and the entire system ($\delta_{Z/T}$):

$$\delta_{\text{Zone}} = \frac{Q_{L-\text{Zone}}}{Q_{\text{IN}-\text{Zone}}} \times 100\% \tag{4}$$

$$\delta_{Z/T} = \frac{Q_{L-\text{Zone}}}{Q_{L-\text{Total}}} \times 100\% \tag{5}$$

where $Q_{L-\text{Zone}}$ volume of water lost in a given zone, $Q_{\text{IN}-\text{Zone}}$ volume of water pumped into a given zone, $Q_{L-\text{Total}}$ volume of water lost in the entire water supply system.

The second task of the diagnostic method was based on the cooperation of SCADA and numerical model of the water supply system, realised by means of the GIS database. Constant comparison of the results of simulation calculations with the indications of the sensors monitoring the system operation constitutes the core element. This comparison simultaneously encompasses all the sensors installed in the system. The permissible difference between the calculations and measurements was assumed as ± 5.0 m H_2O pressure height and ± 9.0 m^3/h (25% of fire hydrant capacity required by local fire brigade) or $\pm 10\%$ of water flow intensity. The 10% threshold was assumed in the places where the flow intensity is so high that the 9.0 m^3/h difference approximates the measurement error of the monitoring sensors. The adopted alarm thresholds resulted from the assumptions agreed with the operator of the water supply network. The proposed diagnostic tool should inform the network operator about sudden, significant anomalous conditions requiring the prompt dispatch of repair teams. Continuous leaks with lower values are captured by the actions shown on the left side of the diagram in Fig. 3. The values of the alarm thresholds resulted from the experiments carried out in the analyzed water supply system. During them, hydrants were opened in each zone, measuring their outflow, as well as controlling the indications of the functioning monitoring system.

In the case when the calculated difference between the results of simulation calculations and the indications of measurement sensors exceeds the afore-mentioned thresholds, the elaborated informatics tool generates the alarm warning the dispatcher about a potential emergency. Then, the dispatcher decides either to cancel the alarm or implement the procedure of leak identification using a specialised WaterGEMS module of numerical model of the water supply system. This is the third task of the proposed method searching of the leakages location.

In the course of normal water network functioning, there are situations where repair teams need to introduce changes in the direction of water flow and temporarily shut down part of the pipes. In this case, the alarms would result from changed, rather than abnormal network operation. While designing the diagnostic system, it was also necessary to implement averaging of the collected measurement data. The installed monitoring system operates with a short, 10 s time-step. However, momentary increases/decreases of the measured parameters should not trigger alarms. Therefore, in agreement with the water supply company, a decision to average the measurement data in 20 min intervals, was made. These intervals were correlated with the time-step of the numerical model.

The numerical model is one of the more important elements of the described diagnostic method. It was built using the WaterGEMS software by Bentley, due to its compatibility with the existing GIS database, automated calibration procedure, and specialised module enabling leakage identification. The model was based on the automatic conversion of data from outside the GIS database. The model includes all pipes and the largest house connections. While building the basic version of the model, the necessary characteristics of the pumping station, reducing valves, and network tanks were entered manually. However, the basic version of the model requires periodic updates connected with the changes in base demand, as well as with the changes in the status of network valves. Water demand patterns include one week (7 days). Every week the base demand of the recipients is being updated. The network valves status is updated every day. The built informatics tool enables to perform these updates automatically, requiring the operator to issue only a few commands. Prior to implementation, the model was calibrated twice, accounting for the equivalent roughness of pipes and hydrant tests. The calibration process was performed in accordance with the ECAC/AWWA standards (AWWA 1999). The process of updating and calibrating the model has been largely automated thanks to a properly prepared GIS database (special layers including valves status, water demand by recipients, demand patterns of significant and characteristic recipients, registration of monitoring data, etc.). This process takes approximately 6 h. Its implementation is planned at 3 month intervals.

Results and discussion

Task 1: water loss assessment

The method combined with an informatics tool presented above has been applied at the beginning of 2020. The three-month observation period was considered a pilot run, which aimed at checking the correctness of operation,

identifying the problems with functioning, and planning the utilised system modification.

The water loss indicated by the diagnostic method was variable during the analysed 3-month period (Fig. 4). Twelve major malfunctions occurred in that time, with the largest on 26th of March.

Implementation of the diagnostic method enabled to identify the zones responsible for the majority of occurring water losses. For example, the central zone "Old city", generated up to 75% of losses in the entire system (Fig. 5).

The zones located at the outskirts of the city were responsible for much lower amounts of lost water. Exemplary diagnostic method indications for such zone were presented in

Fig. 6. This zone generated less than 1.0% of losses determined for the entire system.

Task 2: detection of abnormal network functioning

Following the launch of the diagnostic method, the dispatcher acquired a new decision-aiding tool. Thirty three flow meters and 44 manometers are used for this task. Figure 7 shows the exemplary summary screen of generated alerts in chronological order. The system operator can freely define the time period from which these alarms come. Figure 8 is an exemplary graph comparing the observed and calculated flow rate results, along with identifying the period during which the differences in these values generated an
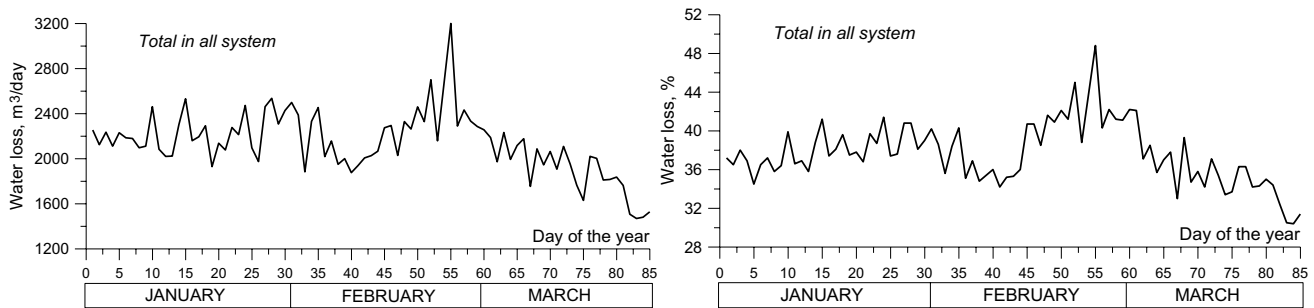
Fig. 4 Volume of water lost in the entire water supply system in 2020 in m^3 (left) in % of water production (right)
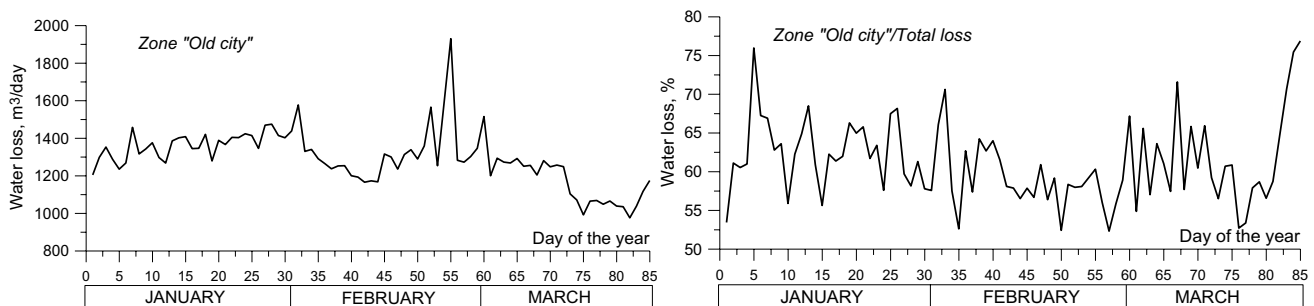

Fig. 5 Water losses in the "Old city" zone, in m^3 (left), as percentage ($\delta_{Z/T}$) in relation to the losses in the entire water supply system (right)
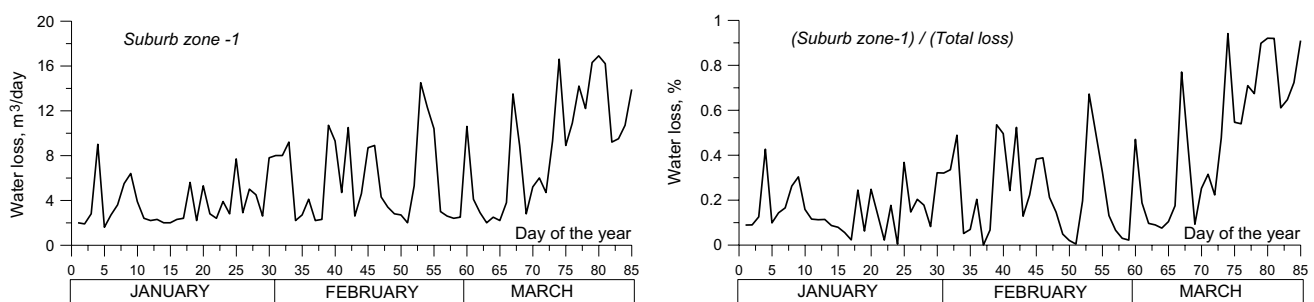

Fig. 6 Water losses in "Suburb-1" zone in m^3 (left), as percentage ($\delta_{Z/T}$) in relation to the losses in the entire water supply system (right)
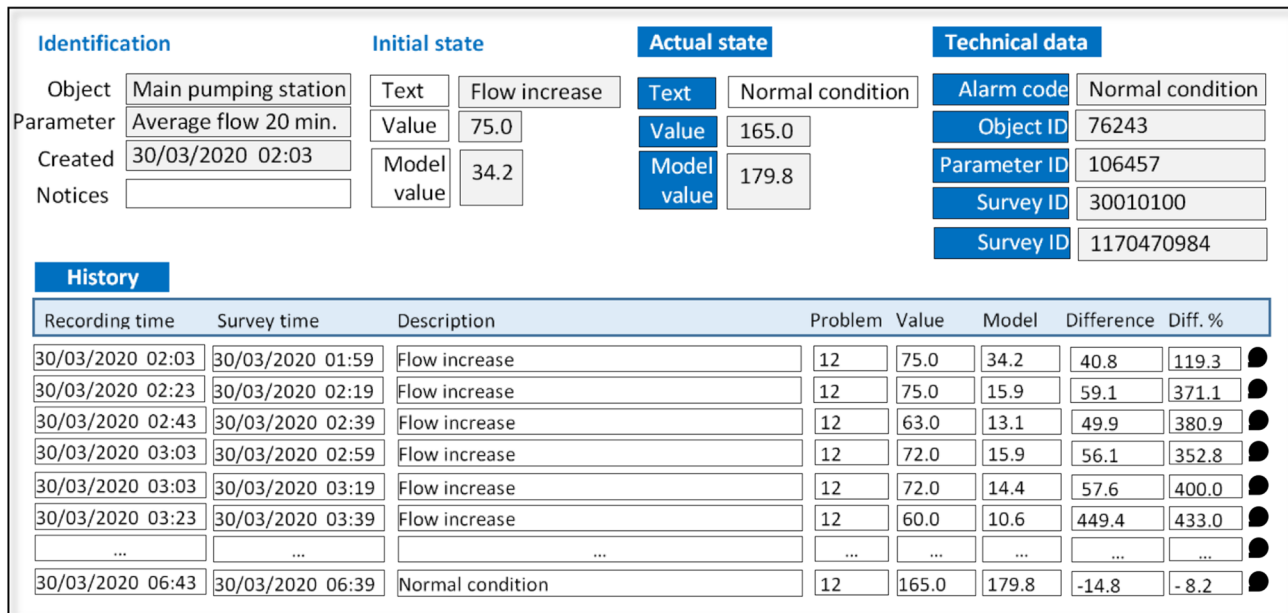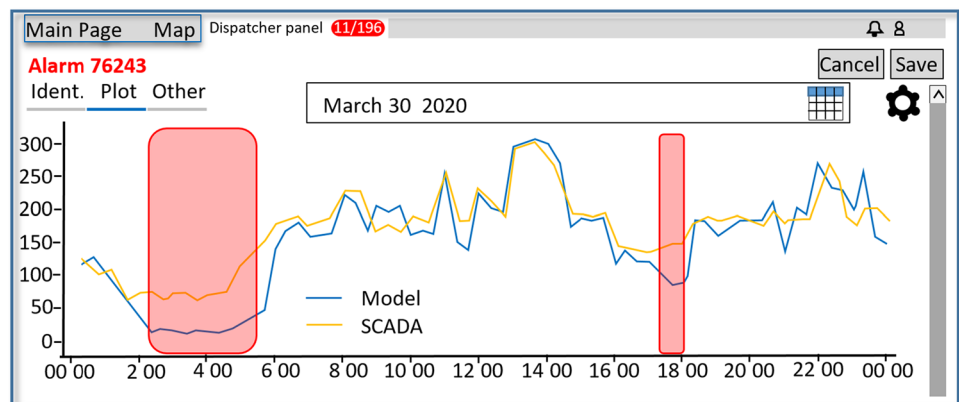
Fig. 7 List of alarms from 30th March 2020 screenshot

Fig. 8 Details of an exemplary alarm screenshot

alarm. The operator may define a time period to include these comparisons. This screen is called by the operator by indicating the selected alarm presented on the screen in Fig. 7.

In the course of a 3 month observation period, the majority (98%) of alarms raised by the presented diagnostic system resulted from exceeding the 10% threshold of differences in the indications of flowmeters and results of simulation calculations. The authors believe that the alarms raised in that time result from the change in the method of allocating water to losses particular recipients. With no knowledge of the losses locations at the start-up of the numerical model, the base demand of each recipient was increased by an identical water loss resulting from dividing the total losses in the entire system by the number of recipients. This losses allocation way is characterised by an additional disadvantage

the losses change in line with the water demand pattern of a given recipient in numerical model. At night, the values of this demand are the lowest. The second probable cause of raising numerous alarms corresponded to breaking the declared network tank filling regime by the company employees. Despite the existing automatic control system, the employees periodically apply "manual" regulation, sometimes without informing the network dispatcher. The third probable reason for the alarms in hours other than night is the lack of implemented water demand prediction model. This resulted from a deliberate postponement due to financial reasons, made by the company. However, it necessitated at least monthly update of base demand, allocated water loss, as well as the demand change models.

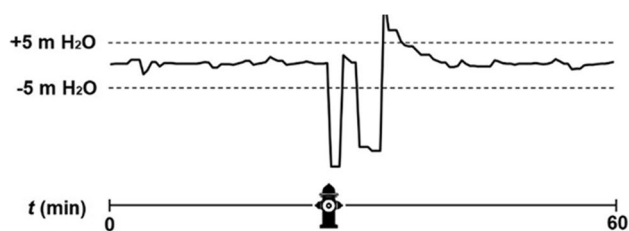The fact that the alarms raised also as a result of exceeding ± 5.0 m H_2O pressure head difference in the

Fig. 9 Graph of the recorded pressure value changes during the test hydrant opening

Fig. 10 Indication of the most probable leakage location in the analysed zone

indications of network manometers in relation to the values obtained via simulation calculations, is noteworthy. In the analysed period, only 12 events caused the pressure drops which were substantial enough to exceed the limit value. The lack of alarms may stem from a significant oversizing of WSS pipes in relation to the current needs. It may also be the outcome of an erroneously assumed alarm threshold.

Task 3: searching of the leakages location

To check the possibilities of leakage location the authors performed the fire hydrant opening trials in the presented observation period. Figure 9 presents exemplary results of such test conducted in a selected small zone. The zone was supplied via its own pumping station, equipped with a flowmeter (Q) and a manometer (p). No other measurement sensors were found in that zone. The hydrant opening was shorter than the 20 min time step of the diagnostic method; hence, it did not trigger the alarm. Short opening time stemmed from the water conservation practice. However, it was enough to be registered by the monitoring system. This enabled a test start-up of the leakage detection module, which constitutes an essential element of the proposed diagnostic method.

The leakage detection module (WaterGEMS) indicated several probable locations, from the most probable one to second-and third-order locations (Fig. 10). In the case of the exemplary zone, the most probable indication corresponded to the hydrant connection junction. Out of the 24 hydrants opening one in each network zone such good or comparable leakage indication results were obtained only in half of the cases. This indicates the limitations of the leak search function of the proposed method these limitations mainly resulted from an insufficient number of manometers or/and network flowmeters. The existing measurement system did not record the hydrant openings in extensive, complex zones. Therefore, a gradual expansion of the monitoring network is necessary, as far as the financial capacity of the company permits.
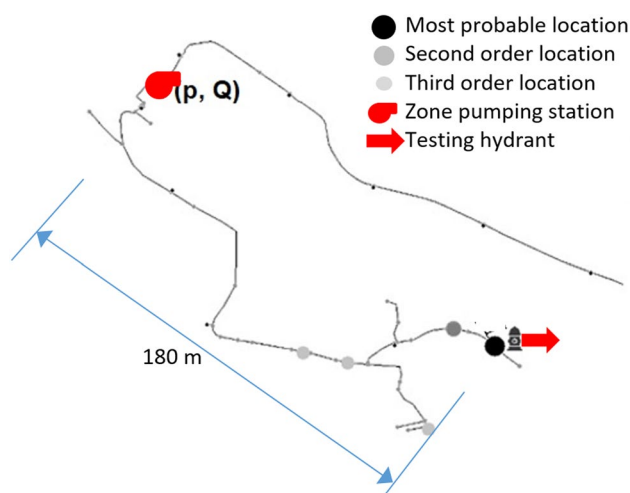
Conclusions

The presented diagnostic method was implemented in existing, highly complex water supply system. It turned out to be a very useful, practical tool supporting the work of the water system dispatcher. The method is still under development. However, it still may be an implementation example for other water supply companies. It's functioning in the first three months was treated as pilot run, necessary to test, find faults and correctly determine the alarm thresholds.

The implementation of the proposed diagnostic tool, already at the pilot stage, made it possible to identify not only the amount of water losses but also their spatial distribution in the network. The implemented system warning about the excessive or insufficient flow and pressure significantly aids the dispatcher in managing the water supply system. It no longer requires constant monitoring of sensors and interpretation of their indications. The application of the leakage detection module facilitates the decision-making process pertaining to dispatching repair teams.

The experience gathered during the first months of implementation of the proposed diagnostic method indicates the need for its modification and development. These include a change in the water loss allocation to particular recipients and implementation of a fully-automated system of managing the network tank filling. Due to the lack of the base demand prediction system, periodic (weekly) updates of the WSS numerical model, accounting for base demand, water losses, and models of changes in water demand, are required. The full implementation of leakage detection requires an increase in the number of pressure and flow sensors, especially in large, geometrically complex zones.

Declarations

Conflict of interest The authors declare no conflict of interest.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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