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MODELING OF WATER AGE CHANGES IN WATER DISTRIBUTION SYSTEMS IN TIME AND SPACE

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ABSTRACT: The paper presents a particularly important research variant in the process of modelling water distribution systems (WDS), which is the age of water. The age of the water in the pipes is a parameter that determines the freshness of the water. The main goal of the presented research was to analyse changes in water age by observing the basic parameters: pressure and water flow. As a result of the assumed simulations, potential places of secondary contamination were distinguished. The result of solving the situation was the introduction of all works aimed at eliminating and improving the negative changes by much more frequent monitoring of water in this area for physicochemical and bacteriological properties and regular flushing of pipelines. The research is carried out based on the mathematical model of the water supply network. The Epanet software is used as a research tool, which allows modelling changes in the age of water in the entire water distribution system over time. The basis of the conducted research became the time factor, which plays a particularly important role in the process of managing the water distribution system. Taking into account the time, it was observed how much water remains on a given section from the moment it flows from the inlet and is mixed with water already present throughout the network. A number of simulation options were analysed in terms of the operation of the water distribution system, where the key problem was water stagnation. It should be noted that stagnation of water is particularly dangerous in the case of WDS, the obtained results showed visible places on the tested model. Simulations lasting more than 8, 10 days showed a clear deterioration in its quality. The above studies are of particular importance from the point of view of managing the efficiency of the water supply network. The analysis of water in water supply systems, stagnating and thus ageing, shows that the efficiency of the system significantly decreases. The variability of conditions in the water distribution system also makes the performance of WDS, and especially of pumping units, variable.

KEYWORDS: mathematical model, water distribution system, bacteriological properties, water ages, fresh water flows

Introduction

Research on the operation of the water distribution system is primarily a thorough analysis of the operation of its individual elements, which requires constant discoveries and studies as the problem of its variability over time has not been fully resolved so far. Design, construction and operation are among the main elements of the technical process of waterworks. The latter element guarantees the standard of provided water supply services. The operation has an impact on the rational and effective management of devices, buildings, networks and water supply systems. Water supply systems are classified as critical infrastructure because, in normal, emergency and crisis situations, they play a key role in ensuring the safety of citizens.

The use of computer modelling in water companies is already a common standard. Implementation of the application allows for the organisation of the operating costs of water and sewage systems, increasing the efficiency of enterprise management and supporting the investment process. Having information about the operation of the water system is the basis for the proper functioning of the enterprise. Therefore, it seems advisable to use the hydraulic model of the water supply network as a tool supporting the operation process of the water supply system.

System modelling is based on the most reliable reconstruction of real working conditions, taking into account the variability of water consumption and its distribution. The introduction of more data allows for the rebuilding of the working conditions of the water supply network for random events, i.e. water abstraction for firefighting purposes, breakdowns, and their impact on other recipients of the water supply network (Ostfeld et al., 2011; Marchi, 2012). The hydraulic model of the water supply network gives excellent opportunities to make informed decisions regarding the modernisation, operation and expansion of the water supply system, but most of all, computer support is a guarantee of the smooth functioning of the model (Butler et al., 2016; Gora, 2011).

The scope of considerations carried out in order to obtain the most dynamic character of the work of WDS is modest, and the process of reaching the final results is too simplified. The work undertaken so far covers the vast majority of issues related to the assessment of the functioning at the stage of designing water distribution systems (WDS). As part of the research issues, the results of the analysis of statistical data on damage are presented (analysis of types and causes) and observed under steady-state conditions, and therefore limited to appropriately selected water uptake values (Sitzenfrei et al., 2011).

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Research methods

Water supply for the research area

Computer simulations were carried out using the Epanet software (Rossman, 2000), generally available in scientific and professional environments. Digital maps were used to map the network of pipes with exact diameters, lengths and ordinates. In the process of creating the model, the results of field tests were used, which enabled the adjustment of the values and their parameters to real conditions. Pressure measurements were the basic part of these tests. The obtained data allowed for the calibration of the models. The article pays particular attention to the variant concerning water age changes and conducts a simulation analysis to regulate the pressure and water flows.

Currently, the demand of the studied area for drinking water and other social, living and economic purposes is covered from three water intakes located in different parts of the analysed area. The study was conducted in an area with altitudes from 120 to 130 m above the sea.m level, located in north-eastern Poland, in the North Podlasie Lowland, above the Upper Narew Valley (Figure 1). The area is located in the buffer zone of the Narew National Park. Deep water intakes are located in:

- water supply station No. 1 (production 525 m^3/d, pressure 3,8 bar),
- water supply station No. 2 (production 173 m^3/d, pressure 3,8 bar),
- water supply station No. 3 (production 667 m^3/d, pressure 3,8 bar).

The total length of the cable network in the commune is 23 km. Population: 16,167.

Figure 1. The area of activity of the water distribution system

Source: ZWiK in Lapy, Poland.

In the process of creating the model, the available results of field research were used, on the basis of which the values of individual elements of the system and their parameters were adapted to the actual operating conditions. A fundamental part of these studies were pressure measurements. The obtained data allowed for calibration of the models made.

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Water cutting in individual nodes was obtained on the basis of a previously prepared database that is reading from water meters containing data on the average daily water consumption. The average daily breakdowns in the network nodes were determined by grouping by address.

The model of water supply networks was made using the Epanet software. The basis for building the model was a raster map, processed into a primer for a computer model.

The WDS research model consists of 248 nodes, 3 reservoirs, 315 pipelines, 3 pumps (Figure 2). Total length of sections: 51 312 m.

Losses in water flowing through the pipeline due to friction against the walls were calculated using the Darcy-Weisbach formula (1) (Rossman, 2000):

$$h_f = f\left(\frac{L}{D}\right) \times \left(\frac{v^2}{2g}\right), \tag{1}$$

where:
h_f – the function of head loss (m),
f – friction factor,
L – length of pipe work (m),
d – inner diameter of pipe work (m),
v – velocity of fluid (m/s),
g – acceleration due to gravity (m/s^2).

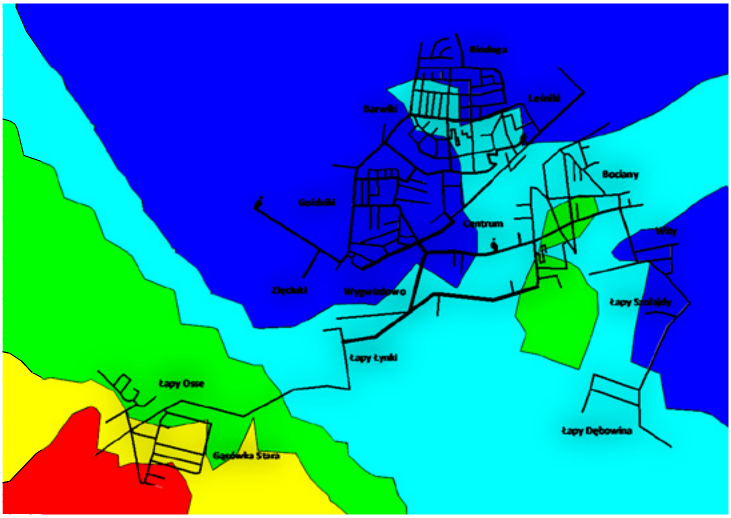

Figure 2. Numerical model of the water supply network, taking into account the height of the terrain

It should be noted that despite the above actions, the received model slightly deviates from the actual conditions. The reason was the lack of com-

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plete data on the materials from which the pipelines are made and the time that has elapsed since their installation, which results in an inconsistent degree of pipe roughness. Creating a model supplemented by these values would require time-consuming field research and studies on the archival documentation of the network.

For research purposes, the degree of roughness for new pipes and uniform roughness values of steel and plastic pipes were assumed.

Results of the research

The water distribution system has been designed for a much greater demand than the current one. The reason for the decreasing consumption is, first of all, the decline of local industry, negative birth rate and impoverishment of the population. As a result, the current water supply network is oversized. Water flow velocities in most sections of the network are lower than the recommended 0.5 m/s, and even the phenomenon of water stagnation occurs. In fear of secondary water pollution, the manager is forced to take preventive measures – washing the network and developing strategies to improve water quality by rebuilding the network. The reconstruction of water intakes is considered to be the most important problem at present. It is considered to switch the supply of the network from the three existing intakes to one intake by switching off the redundant ones and putting into operation only one, located in the northern point of the commune.

Fresh water flows into the network from reservoirs or a source. The age of the water in the pipes should be considered as the main parameter in determining the freshness of the water (World Health Organization, 2017). Due to the assumed problem, which is the age of the water, the Epanet software is used, which makes it possible to carry out the assumed tests with great precision, taking into account the parameter, which is the time when the water stays on a given section from the moment it flows from the intake and is mixed with the water already present. on the Web (Muranho et al., 2012; Filion et al., 2007). Epanet software provides modelling of changes in water age throughout the distribution system, which is an added advantage in forecasting and design (Machell et al., 2014).

The WDS analysis carried out, and the research presented in the paper showed areas where stagnant water ages without an outlet and does not give way to fresh water. Water stagnation is particularly noticeable in the northwest parts of the area red (Figure 3). When the analysis lasted 240 hours (10 days), it was noticed that the water in this area is more than 8 days old, which has a particular impact on its quality. Research has shown that this is a potential site for secondary contamination. Due to the results obtained, additional

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measures were taken to monitor the water in this area more often in terms of physicochemical and bacteriological conditions and to regularly flush the pipelines (Diao et al., 2010).

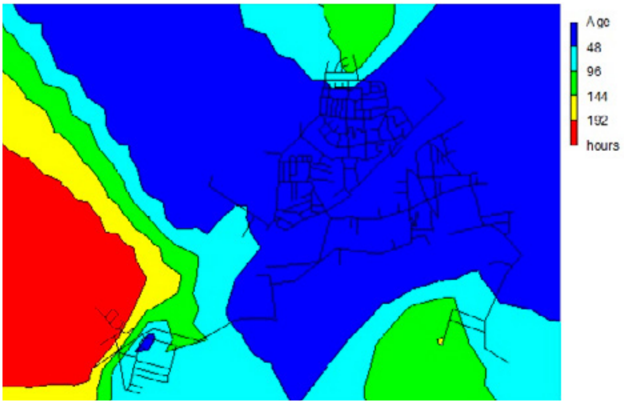

Figure 3. WDS water age during the simulation lasting 240h on the scale of 1: 25,000

Other areas where the deterioration of water quality was observed are the northern district of the area, where the water age may exceed 6 days. The observed situation results from the considerable distance from the shots. These areas are the farthest from the intakes, and naturally, transported water arrives here at the latest.

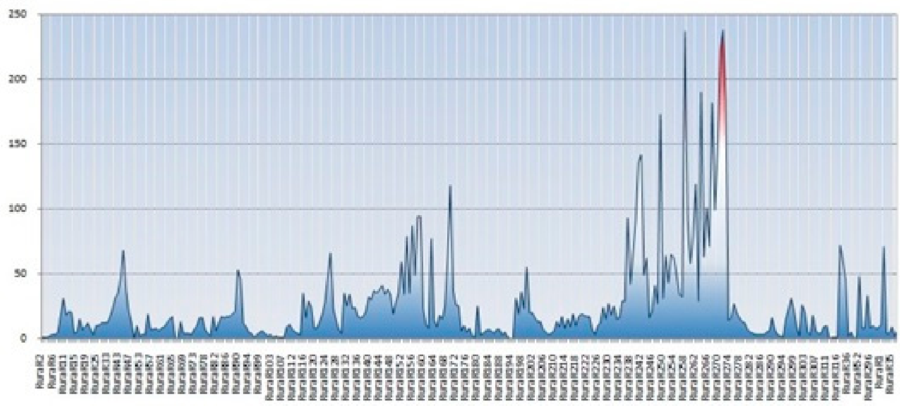

Figure 4. Temporary description of the age of water after a period of 10 days of work

Figure 4 shows a rope that defines the age of water in individual pipes. The differences in height between individual points indicate the degree of variation in the freshness of the water in the network.

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The analysed problem reflects with great precision the time course of water age changes for selected connections (Figure 5). For the R30 connection, it was noticed that the water age stabilised after 40 hours, while for the R264 section, it did not reach a stable value until the end of the analysis.

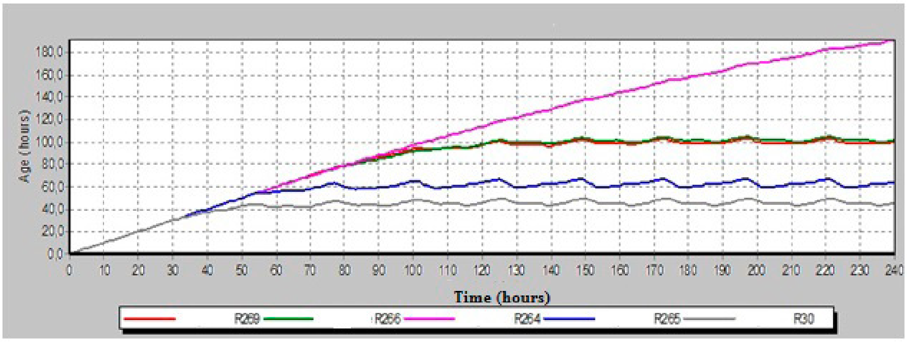

Figure 5. Time course for selected connections

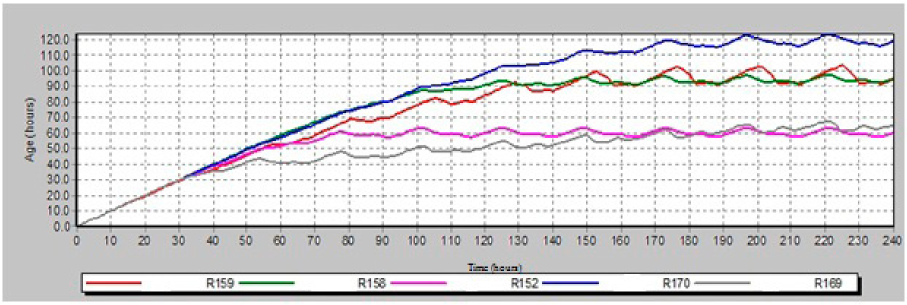

Figure 6. Time course for selected connections due to the analysed location

An important parameter in the model when analysing water quality in terms of age is the duration of the simulation. This fact is very often emphasised in numerous publications. (Masters et al., 2015; Prest et al., 2021). Figure 5 shows that by completing the analysis after 150-160 h, the results could be read by describing the water for the R169 connection as fresher than that flowing in the R152 connection, while the long-er-lasting analysis starts the line transition in favour of the R169 section. A similar situation occurred in the previous example due to the duration of the analysis, where segment R264 did not reach the maximum value of the characteristic curve.

A very helpful research tool of the Epanet software is the ability to instantly find an anomaly in the model under consideration (Machell et al., 2014). It should be noted that a necessary step in this direction is the most accurate reflection of the actual operating conditions of the water distribu-

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tion system. Figure 7 clearly shows sections R258 and R272, in which water stagnation occurs. When analysing the situation involving the insertion of non-return valves in them, no improvement was obtained, hence the conclusion that the manager should consider the possibility of disconnecting the tested sections from use.

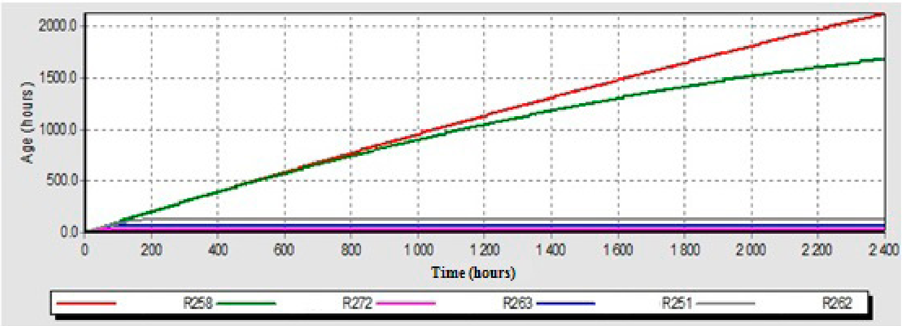

Figure 7. Parameter observation: water age, lasting 100 days

By analysing subsequent possible problem scenarios, a deterioration in water quality due to network oversizing was observed on the developed WDS model. Especially in the northern part of the district, where stale water reaches the recipients. The analysis of the situation shows another advantage of the Epanet software as a tool for monitoring the freshness of water. Generally, until hydraulic calculation software is available on the market, a water freshness report would not be possible without time-consuming field research. The resulting simulation model provides these needed results immediately. It is only limited by the computing power of the machine, and the amount of data initially entered into the calculations. This problem has also been highlighted in numerous publications (Tamminen et al., 2008; Shokoohi et al., 2017).

It should be noted that the problem of research on the change in water age and the related efficiency of water distribution systems has not yet been fully solved. The scope of considerations carried out as part of obtaining the most dynamic nature of the work of water distribution systems is modest, and the process of reaching the final results is too simplified.

The work undertaken so far concerns the vast majority of issues related to the performance assessment at the design stage of the system (Kurek et al., 2013; Diao et al., 2012). This way of considering it has become the subject of many publications, in which the most important point was the development of an appropriate mathematical model and its numerical implementation to precisely determine the functioning of the WDS and, at the same time, affect

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the savings in the time of all calculations. This can be observed in various studies: (Blokker et al., 2016; Butler et al., 2016).

Another factor confirming the complexity of the described problem is time, which is pointed out by the authors of the following publications (Preis et al., 2010; Machell et al., 2014). Sets of corresponding lattice states are formulated, and these states are analysed at a given moment of time (Masters et al., 2015; Filion, 2008). Water should be delivered at any time, depending on the needs of the recipients. As a result of their considerations, the authors of the following publications note this (Machell et al., 2014; Sitzenfrei et al., 2012).

The problems and topics, taking into account the need for further research in this area, have been identified in various studies (Kanakoudis et al., 2019; Shokoohi et al., 2017; Walski, et al., 2003).

The analysis of the current state of knowledge about research on changes in water age and the related functioning of the water distribution system shows that research issues are given much less space than design issues. However, there is no research on the analysis of the impact of basic hydraulic parameters – pressure and water intensity in terms of time and space.

Conclusions

The presented computer simulation revealed the existing deficiencies in the management of the water distribution system of the water supply network in a given area and allowed by mapping the time course of water intake to much deeper information about the operation of the entire system and the possibility of improving its functioning. It has become a helpful tool enabling the development of a method of inferring the variability in time of characteristic parameters of the water distribution subsystem. It reflects their impact on water age changes with great precision and allows for obtaining information about the behaviour of individual real objects based on observation of the developed model of the water distribution system simulating their behaviour.

The analysis of two very important problems, which were: the speed of water flow in the pipes and the analysis of the age of the water in the pipes, required an in-depth analysis. This was mainly due to the fact of checking the correctness of operation with fixed momentary values of parameters without taking into account the events that occurred earlier. Thus, the operating conditions of the water distribution system adopted in the classical method may have never existed in practice, as the actual behaviour of individual elements of the adopted system may have turned out to be different from those adopted for calculations.

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The simulations carried out proved that the analysed network qualifies for modernisation. Thanks to the tool that Epanet has become, it was possible to carry out a number of important and difficult to imagine situations in terms of correct functioning and forecasting possible changes in SDW, find problematic network parameters and consider concepts of engineering solutions.

Based on the results of simulation calculations, the working conditions were first of all developed, with different conservative states. The conditions of WDS operation with randomly occurring failures were mapped, and their impact on the parameters of water intake by consumers was analysed.

The emerging variability of the pumping station's operating parameters and the variability of water consumption by the city have for a long time required the creation and use of a research tool that would allow for the mapping of the dynamic nature of the work because the classic method used so far did not provide such opportunities and in a very cursory manner presented the parameters illustrating the operating conditions of the WDS.

The presented method of computer simulation has cognitive and utilitarian values, and, as a computer technique, it will also be applicable here, pointing to the necessary conditioning of repair works by means of mathematical calculations. The analysis of the results gave a clear goal to optimise the network through modernisation.

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