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CASE STUDY OF FAILURE SIMULATION OF PIPELINES CONDUCTED IN CHOSEN WATER SUPPLY SYSTEM

SYMULACJE AWARII RUROCIĄGÓW PRZEPROWADZONE NA WYBRANEJ SIECI WODOCIĄGOWEJ – ANALIZA PRZYPADKU

The main goal of this work is to simulate the failure of water pipe network, using the hydraulic model of the network created through Epanet 2 program. The model includes the cooperation of the second stage pumping station with the expansion tanks located in the network. Based on these parameters, the simulation operation of water supply network was performed, as well as failure simulation on the basis of closing some sections of water pipe network. Failure analysis allowed to perform characteristics of the water supply system including pressure changes that occur in the network during failure simulation.

Keywords: *water supply, failure, hydraulic model, risk, reliability.*

Głównym celem pracy jest przeprowadzenie symulacji awarii przewodów przewodów wodociągowych, za pomocą stworzonego modelu hydraulicznego sieci z wykorzystaniem programu Epanet 2. W modelu zawarta jest współpraca pompowni drugiego stopnia ze zbiornikami wyrównawczymi znajdującymi się na sieci. Bazując na tych parametrach przeprowadzono symulację pracy sieci wodociągowej, a dzięki wyłączeniem odcinków przewodów wodociągowych symulację awarii. Analizowanie awarii pozwoliło na scharakteryzowanie dostawy wody do odbiorców w tym zmian, jakie występują na sieci podczas symulowania awarii.

Słowa kluczowe: *wodociąg, awaryjność, model hydrauliczny, ryzyko, niezawodność.*

1. Introduction

In the Safe Drinking Water Act (SDWA) passed in 1974 by Congress of the United States the strict regulation for water supply was presented. Also water recipients can get from the Environmental Protection Agency a Consumer Confidence Report which precisely describes the water network functioning, along with potential risks in drinking water network. In spite of incorporating many reports, regulations and standards that public drinking water systems must follow, still many failures occur causing serious effects for water consumers. The main problem that may arise in the operation of water supply systems are breaks in water supply and change in water quality in case of failure when the standard requirements are not met [4, 9]. Risk that users of the water supply system take in such case is the lack of water supply or receiving water with insufficient pressure and inadequate quality [25]. The risk that such undesirable events occur is associated with consumer dissatisfaction [11]. The risk concerns not only the water consumers but also the water producers. From the producers point of view it involves disturbances or interruptions in water production or distribution, which, in turn, causes the financial losses caused by the unsold water, penalties and compensations paid to water recipients [24]. Such situations are caused by the water supply system failures, especially by failures in the main network which have larger consequences and cover larger area, while failures of distributional pipes are important to customers directly supplied from given pipes and the nearest area. To prevent such problems and improve the quality of services provided by water companies, risk analysis should be conducted by hydraulic simulating failures in water pipes [1, 2] and through implementation of intelligent monitoring of water supply system [26, 27]. Currently the requirements relating to water supply increase, therefore the water suppliers should reduce the risk associated with lack of water supply or supply poor quality water [14]. Therefore risk analysis and assessment in municipal systems is commonly used [3, 7, 16, 23]. Determination of the risk associated with failure rate of water supply network consists of several phases, such as the determination of water supply system type, the designation of the failure rate limit, the determination of the difficulty and type of repairs, determining the protection barriers and the risk levels [17].

Risk is generally defined as the expected value of the losses and can be presented by the formula (1) [18]:

$$R = P \cdot C \tag{1}$$

where P is the probability of failure occurrence and C are consequences associated with the probability P.

Failure causes of the municipal infrastructure involve such errors as design errors, both in the hydraulic calculations, errors of exploitation character, e.g. no security resistance, lack of insulation, incorrect compensation, incorrect execution of connections, improper laying of pipes and operating errors such as inadequate strategy of repairs, technical wear, exploiters errors and aggressive or sulfate media influence [3, 12, 13, 19].

Therefore for modelling water mains are used different kinds of programs that are very helpful in solving problems related to the design and operation of water distribution systems [6, 21].

The basic role played by computer models is the hydraulic analysis of water distribution system operation. This analysis may include not only changes in water pressure in the network but also water quality changes in the network via the information about the spread of disinfectant, the cost of the electricity used to pump water [22]. To facilitate the analysis of consequences of failure occurrence and thus the scope and duration or size of restrictions in water supply the hydraulic model mapping the network operation was developed in the program Epanet 2. This model shows the current state of the water demand, together with the current water distribution in the analysed system supplying water for about 180 thousand of residents. In this model also the cooperation of the second degree pumping station with the expansion tanks was presented.

The analysis referred to comparison of the network working without failure for 24 hours with the operation of the network when the failure occurs. The proposed model allowed to determine to perform analysis of operation of the water supply network. The scope of work includes compiling information about the water supply system and making the hydraulic model of water supply network, performing hydraulic simulation of pipeline failure, presentation and summarizing the results of the simulation.

2. Case study of failures in water network based on operational data

2.1. Preliminary assessment of pipeline technical state

The analysed water network is a ring system formed by four mains with total length of 49.8 km. The total length of operated water supply system amounted to 902.8 km in 2016. Figures 1 and 2 show the age and material structure of the considered water supply network.

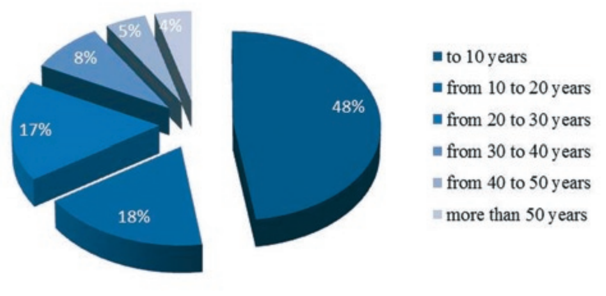

Fig. 1. The age structure of the water network - state for 2016, in %

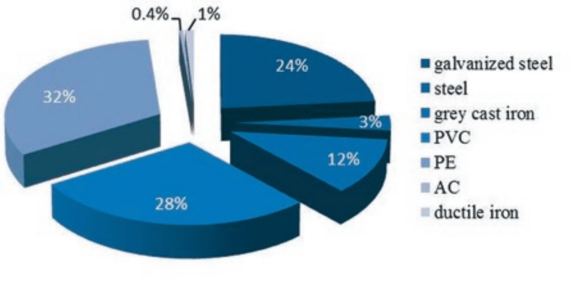

Fig. 2. The material structure of the water network - state for 2016, in %

Data on failures connected with failure time removal in the water pipes in the years 2000-2016 are presented in Fig. 3.

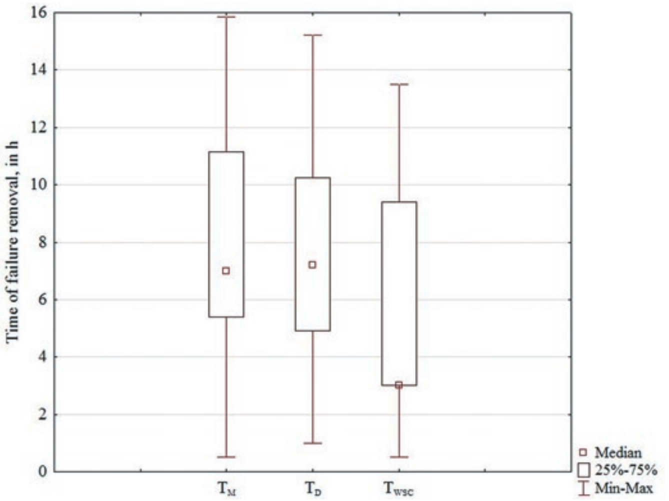

Fig. 3. Time of failure removal in the water supply pipelines in the years 2000-2016 for mains - T_M, for distributional pipes - T_D, and for water supply connections - T_{wsc}

In the Figure 4 the number of failures expressed in percentage depending on the pipe material was presented.

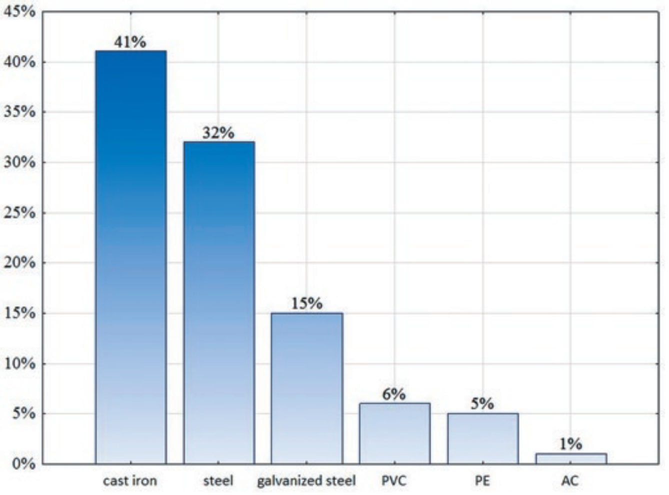

Fig. 4. Failures of water network in the years 2000-2016 with division into failure occurrence and pipe material, in %

2.2. Water network failure

The unit failure rate λ_i, with division into water pipe type, material and type of failure was calculated according to the formula (2) [8]:

$$\lambda_i = k_i / (l_i \cdot \Delta t)$$

where k_i is the total number of failures in one year in a given type of network, l_i is the length of a given type of network in km, Δt is the considered period, one year, and i is the type of water network or type of failure.

2.3. Discussion of results

The average values of the failure rate for different types of network are:

- for mains $\lambda_M = 1.03\ a^{-1} \cdot km^{-1}$,
- for distributional pipes $\lambda_D = 0.34\ a^{-1} \cdot km^{-1}$,

- for water supply connections $\lambda_{wsc} = 0.32\ a^{-1}\cdot km^{-1}$,
- for the whole water network $\lambda_t = 0.56\ a^{-1}\cdot km^{-1}$.

The failure rate for each type of water supply system is shown in the Figure 5.

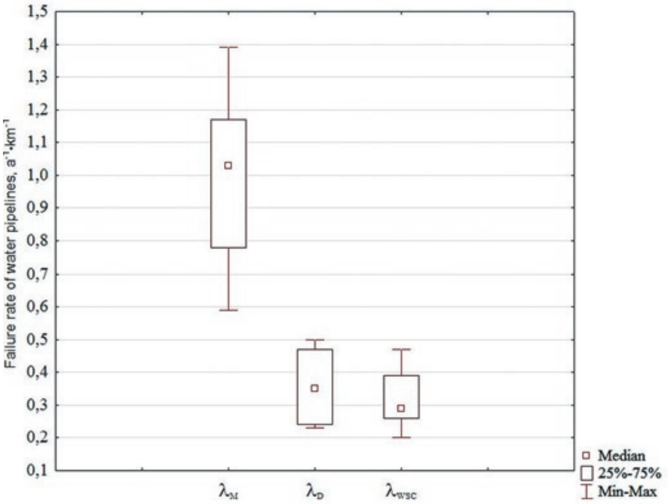

Fig. 5. The failure rate of the mains - λ_M, distributional pipes - λ_D, and water supply connections - λ_{wsc}

Analysing the failure rate it can be stated that in the years 2000-2016 the number of failures and thus the intensity of failures steadily decreases, which in turn can be caused by modernization of the network in recent years and the implementation of new pipes made of more durable materials that are less prone to failures. It can be seen that the highest failure rate is for the mains, it is caused by the pipe age, also by the fact that these pipes are made of iron or steel, which are more prone to failure than PE pipes, for which most old pipes are replaced. The failure rate for the mains should not exceed $0.3\ a^{-1}\cdot km^{-1}$ according to risk criteria given in [15], so it can be concluded that the mains require renovation or replacement. The distributional network and water supply connections do not exceed the limit values for this indicator, which is for the distributional network $0.5\ a^{-1}\cdot km^{-1}$ and for water supply connections $1.0\ a^{-1}\cdot km^{-1}$. Taking into account the material structure of network pipes, the highest failure rate have water pipes made of cast iron ($\lambda_{cast\ iron} = 1.5\ a^{-1}\cdot km^{-1}$) and steel ($\lambda_{steel} = 1.53\ a^{-1}\cdot km^{-1}$). Currently used plastic materials like PVC and PE indicate lower failure rate, respectively, $\lambda_{PVC} = 0.03\ a^{-1}\cdot km^{-1}$ and $\lambda_{PE} = 0.06\ a^{-1}\cdot km^{-1}$. Increased failure rate for specific materials determines the cause of the failure, the highest rates were recorded for the failures caused by corrosion and cracks, the median of mentioned causes amounted to, respectively, $\lambda_{corrosion} = 0.36\ a^{-1}\cdot km^{-1}$ and $\lambda_{cracks}=0.26\ a^{-1}\cdot km^{-1}$.

3. Research methodology

3.1. Characteristics of software used for the simulation of the water supply system

One of the recommended program used for water supply system modelling is program called Epanet 2.0, created by Lewis A. R. for the U.S. Environmental Protection Agency. It is used to design and control the operation of water supply systems. In this program, as in a real network, the following elements can be found: intake, pumps, nodes, different kinds of valves and tanks. The program also allows to track the flow in each pipe or the amount of pressure in the individual node [20].

Work with the program Epanet 2.0 begins by drawing the water supply network model, then the characteristics of elements used to create the tested model of examined water network should be made. They are, among others:

- reservoir (water source for the modelled network). Input data include: determining the location of a reservoir in the diagram, the elevation of the water table above sea level, the quality of water flowing into the network,
- joint (network node which starts and ends pipe). Input data: the location of the joint in the scheme, the elevation of the joint above sea level, the time distribution of water demand in the given node, the number of different categories of water consumption defined for the node, coefficient reducing the flow associated with the applied flange assigned to the node, quality of water entering the network at this point,
- pipe (pipe connecting two nodes). Input data: length, diameter, absolute roughness of the pipe, the loss factor,
- tank. Input data: determining the position of the tank in the scheme, the position of the tank bottom above sea level, the initial water level, the minimum and maximum determine the level of water in the tank, diameter, minimum volume, volume curve, mix model, initial quality and source,
- pump. Input data: coordinates, identifier of a node in which the suction line begins and ends, the characteristics of the pump flow, power, velocity, technical data of the pump, the characteristics of efficiency, energy price - the price for energy calculated implicitly for kW/h, the cost of energy for one day.

In this study only the results of modelling the tested water supply system based on the hydraulic and time characteristics are presented.

3.2. Hydraulics of water supply network

To help minimize the consequences of the failure of the water supply pipeline and hence range, duration and size of interruptions in water supply the hydraulic model was developed in the Epanet 2, mapping the network operation. It allows to simulate failure of individual network sections defining the scope of the impact of the section exclusion on the network operation.

It should be noted that the water supply system constitutes a set of interrelated elements which work affects other elements. The parameters which describe the operation of these elements are, among others, the flow rate, pressure, flow resistance. The consequences of such structure is the need for modelling the entire water supply system [5, 9, 10].

Before performing the simulation the water demand was updated for each node of the model. Pipes of the model are assigned to individual streets along which they are laid, in accordance with the updated map obtained from the water company. In the model, a number of water meters in the street and the number of inhabitants supplied from the given pipe, were determined. The value of the individual water demand was established after taking into account the work of tanks, reservoirs and therefore cooperation with the pumping station, readings of water meters and water level fluctuations in the expansion tanks. It allowed to determinate the daily and hourly water demand.

In case of high buildings which are supplied by hydrophores the data were obtained from the water company. High impact on the water demand have the industrial plants, which were also included in the analysis after receiving the detailed data from the plants.

The presented simulation covers one day of largest consumption in the water network, 24 hours beginning from 6 a.m. With the model it is possible to perform the analysis of the consequences of network pipe failure by comparing the pressure in the nodes of the network during normal network operation and during failure occurrence.

Before performing calculations on the network model the tare was conducted which involved determining the characteristics of the second stage pumping station to illustrate real city's water supply and to compare the determined pressure in the network to the real conditions, taking into account the information obtained from network monitoring. To calculate the hydraulic losses the Darcy-Weisbach formula was used.

3.3. Determination of the risk associated with the failure rate of the tested water network using two-parameter method

Using the calculated failure rate the risk of failure in water supply network can be calculated. For calculating risk the two-parameter method was proposed according to the equation 1.

The probability of failure *P* can be determined by multiplying the failure rate, the pipe length and pipe renewal time (Eq. 3):

$$P = \lambda \cdot l \cdot t \tag{3}$$

where λ is the failure rate for each pipe, ($a^{-1} \cdot km^{-1}$), L is the length of the examined segment of pipe (km) and t is renewal time of examined segment of pipe, (a^{-1}).

The consequence of failure is the number of inhabitants without the access to water, so the risk was determined according to Eq. 1 by multiplying the consequence and failure probability.

The limit values of risk have been adopted on the basis of the analysis of the operational data of the analysed water supply system. The limit value of tolerable risk was determined by multiplying the probability of failure falling on one segment of the distribution network and the number of residents cut off from water supply per one section of the network, respectively $R = 0.085$. The limit value for controlled risk has been adopted for the main network and amounted to $R = 0.62$.

4. Results of the model analysis of water supply network in the Epanet program

The first step was to analyse all the studied sections and turn off each of them. Examples of the results of the pressure head difference in the nodes were shown in Table 1. Due to the large amount of results only part of them was presented and selected hours with the highest demand for water in which there was the highest pressure drop.

In most cases, the pressure head difference in the examined nodes before and after the failure is insignificant, which indicates that the failure will affect only the residents directly supplied from the pipeline, it is caused by the fact that the water supply network is constructed as a ring . Because the analysis contain large amount of results, for nearly 300 pipes, only some failures were selected to present in order to indicate their consequences, as shown in Table 2.

In a detailed manner the simulation results for two pipes located in various parts of the city whose exclusion causes a significant decrease in pressure at the site of the failure and its surroundings, were presented. Such pipes were chosen whose exclusion caused head drop of more than 1.0 mH_2O.

Results during operation with and without failure are presented on the Figures 6-9.

In the presented sections of pipes the risk value exceeded the tolerable level. In the section no. 1571 with a length of 104.4 m and a diameter of 300 mm, the failure causes that 5940 inhabitants are without water supply for $R = 0.4885$.

The largest pressure difference in this pipe, before and after failure, occurred in the node 157 at 6.00 and 10.00, and reached 5.01 m, from the value of 34.72 mH_2O to 29.71 mH_2O at 6.00. On the other hand, in the section 98 the biggest pressure difference before and after failure occurred in the node 102 at 6.00 and amounted to 7.90

Table 1. Part of calculations obtained by modelling each node during operation without failure and during failure in selected hours of highest water demand generated by using Epanet

State before failure		State after failure		State before failure		State after failure	
Time [h]	Pressure head [m]	Time [h]	Pressure head [m]	Time [h]	Pressure head [m]	Time [h]	Pressure head [m]
Table of time series – Nod 503				Tabela serii czasu – Węzeł 750			
00:00	32.30	00:00	28.16	00:00	29.73	00:00	26.05
00:01	32.27	00:01	28.38	00:01	29.74	00:01	26.28
00:02	32.07	00:02	27.99	00:02	29.51	00:02	25.88
00:03	32.03	00:03	28.14	00:03	29.49	00:03	26.04
00:04	31.83	00:04	27.75	00:04	29.26	00:04	25.65
00:05	31.80	00:05	27.98	00:05	29.27	00:05	25.88
00:06	31.76	00:06	28.13	00:06	29.26	00:06	26.03
00:07	31.86	00:07	28.69	00:07	29.42	00:07	26.61
⋮							
Table of time series – Nod 1229				Table of time series – Nod 750			
00:00	33.05	00:00	29.76	00:00	22.58	00:00	15.00
00:01	32.96	00:01	29.54	00:01	22.60	00:01	15.48
00:02	32.75	00:02	29.25	00:02	22.36	00:02	14.90
00:03	32.85	00:03	29.12	00:03	22.36	00:03	15.24
00:04	32.68	00:04	28.88	00:04	22.12	00:04	14.66
00:05	32.69	00:05	28.74	00:05	22.14	00:05	15.13
00:06	32.64	00:06	28.60	00:06	22.13	00:06	15.46
00:07	32.73	00:07	28.55	00:07	22.31	00:07	16.49

Table 2. Part of the analysis of the sections of distribution network included in the hydraulic model along with the risk calculated by means of the two-parameter method

L.p.	No of section in Epanet	Street name	Diameter [mm]	Lenght [km]	LM [-]	Risk value
	Remarks about pressure in the nodes involved in the section with failure					
24	1402	Baczyńskiego	150	0.4037	67	0.0043
	The highest increase in pressure occurred in the node 313 at 12.00 a.m. by 0.46 m and the highest drop in pressure at node 1308 at 12.00 a.m. by 1.81 m.					
69	1682	Kościuszki	300	0.0802	89	0.0073
	In the node 24 changes in pressure of several cm. Node 1586 pressure drop at 10.00 a.m. of 1.83 m. Node 1587 pressure drop at 10.00 a.m. of about 1.71 m.					
105	1577	Żółkiewskiego	300	0.6299	100	0.0082
	Node 1487 pressure drop at 1.00 p.m. of 1.66 m. Node 164 increase in pressure at 1.00 p.m. of about 1.43 m.					
124	709	Hetmańska	300	0.116	80	0.0066
	Node 650 increase in pressure at 9.00 a.m. of 1.16 m. Node 391 pressure drop at 2.00 p.m. of about 1.86 m.					
221	98	Łukasiewicza	200	0.214	386	0.264
	Node 102 pressure drop at 6.00 a.m. of about 7.90 m. Node 7 increase in pressure at 6.00 a.m. of 0.32 m.					
239	21	Kochanowskiego	300	0.2056	302	0.0234
	Node 350 increase in pressure at 6.00 a.m. of 0.42 m. Node 1485 pressure drop at 6.00 a.m. of about 5.09 m.					

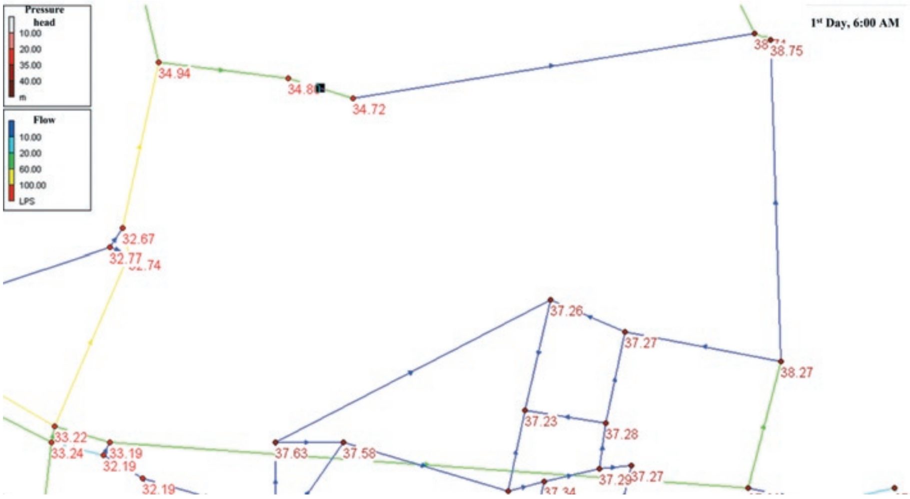

Fig. 6. Simulation of network state before failure - pipe section no 1571

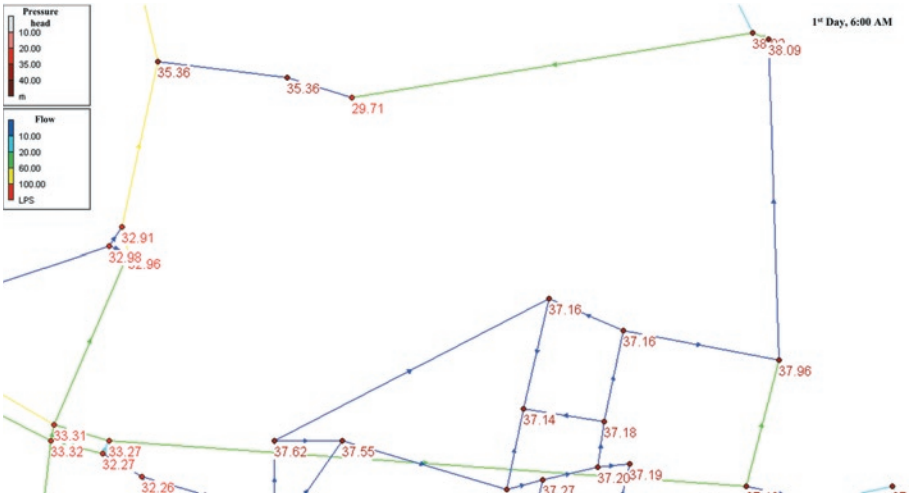

Fig. 7. Simulation of network state after failure - pipe section no 1571

mH_2O from the value of 26.66 to 18.76 mH_2O. Pipe no. 98 supplies water to approximately 386 inhabitants and is characterized by the risk equal to 0.1123. For 23% of examined pipes the risk value exceeds the tolerable risk.

The risk of the tested water supply system takes a small value because during failure of individual water pipes, water is cut off only to the recipients being supplied from those pipes, however, those values are quite large reaching, in extreme cases, several thousand residents without water supply. After detailed analysis of the hydraulic model, it was found that the pressure in the nearest area does not fall enough to cause problems with water supply. A major impact on this situation has also a ring structure included in the model and oversizing of the water supply network.

5. Conclusions and perspectives

The high degree of independence of the network from the failure of individual pipes is probably due to significant oversizing, as well as a significant decrease in water demand, which is now less than 50% of demand in the early nineties of last century. This concerns for example all Polish urban water supply systems developed at least since the sixties, but not in these water systems, which were built since the eighties of the twentieth century.

The performed research was focused on depiction of the hydraulic network, recipients' failure nuisance and real data operation of the exemplary case study water network, during normal and failure event operation. The proposed methodology can be implemented in functioning assessment of any network, dealing with large number of different variables and ob-

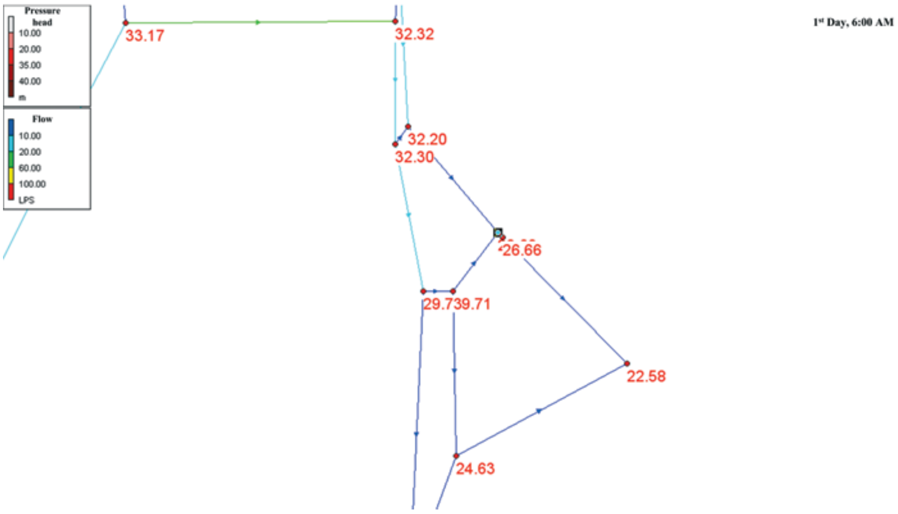

Fig. 8. Simulation of network state before failure - pipe section no 98

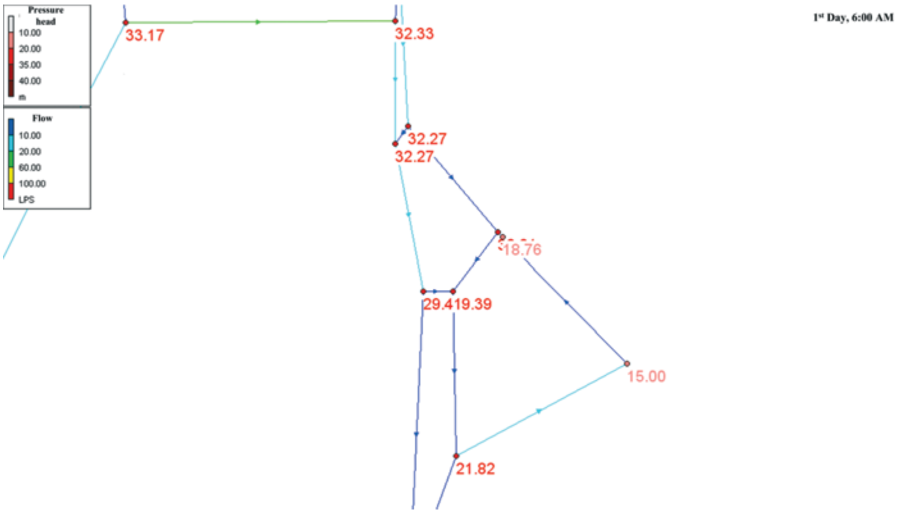

Fig. 9. Simulation of network state after failure - pipe section no 98

tained network information, as to simulate different scenarios and optimize the system. The program used in the analysis does not include cost analysis, but this factors were not used in the consideration of problem with reliable water supplying to recipients. It is worth to underline the possibility of the program to establish the demand fluctuations at each node, as a result of failure occurrence, along with place determination of water supply objects as for example tanks.

A major limitation of the method is to have the revised hydraulic model of water supply network, the construction of which is time-consuming, requires a series of data, which many water supply companies does not possess, as diameter and absolute roughness of pipes built in the first half of the twentieth century, and finally the need to calibrate the model. In practice, only a few waterworks have verified the hydraulic models that can be used in the presented method.

The performed analysis can be an important method to point out the segments of water pipe network which should be modernized in the first place because of their major importance for the recipients, in future research supported by different software through significant performance indicators. Such segments cause the most noticeable for water consumers losses - hence the need for a particular focus on their performance, including qualifying for the reconstruction or renovation. The presented method does not cover all factors influencing the decision-making processes in the activities of the operating water pipes, an outstanding example is the earlier pipe reconstruction cables, despite satisfactory technical state technical, due to the road reconstruction. However this method indicates, however, courses of the water supply system operator in order to achieve the best technical result in the assumed operating conditions of the system.

The presented method and the results are the basis for further studies on risk in quantitative terms, and can be used in the operating practice of water company exploiting the tested water supply system, both with inclusion of internal, external, and environment factors of water supply functioning. Issues outside operation will be covered by different criteria of crucial variables as for example backfilled soil or installation place, through implementation of multi-criteria methodologies and alternative machine learning methods, will constitute the important tool for maintenance support. In future research, the simulation of water network failure will be performed along with cost and economic analysis, based on the past event experience.

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