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KRZYSZTOF BORYCZKO[1], BARBARA TCHÓRZEWSKA-CIEŚLAK[1]

ANALYSIS OF RISK OF FAILURE IN WATER MAIN PIPE NETWORK AND OF DELIVERING POOR QUALITY WATER

The method of identifying areas of risk of failure in water pipe network has been presented including presentation and analysis of risk factors for failure in water main pipe network, the proposal of the method for identifying risk areas using a simulation model of the water distribution subsystems (WDS) operation, and an example of application. In the hydraulic model, the failures of main water pipes as well as the operation of the WDS in the case of contamination were simulated. The proposed method consists of preparing the so-called risk maps and the designation of areas in which the limit values for the identified risk, the first type and the second type according to the assumed risk categories (tolerated, controlled and unacceptable) were exceeded.

1. INTRODUCTION

Urban water system has to provide consumers with drinking water in adequate quantity, at the required quality and pressure corresponding to current standards. Access to safe drinking water is essential to health, a basic human right, and a component of effective policy for health protection [1]. Water consumers are exposed to risk associated with the operation of the water distribution subsystem (WDS) [2–6]. The consequence of failure in water pipe network can be a break in water supply for a specified number of consumers or a drop of pressure in water pipe network below the required value [7], resulting in a lack or reduction of water supply to consumers, especially for those who live on higher floors of buildings.

Another threat for water consumers, apart from the lack of water, is water quality. The source of water pollution in the water pipe network can be the so-called primary

[1]Department of Water Supply and Sewage Systems, Rzeszów University of Technology, al. Powstańców Warszawy 6, 35-959 Rzeszów, Poland, corresponding author B. Tchórzewska-Cieślak, e-mail: cbarbara@prz.edu.pl

contamination. Primary contamination is caused by biological or chemical contamination in source (river, lake, well). It appears in the water pipe network despite water treatment process. Microorganisms can enter the water pipe network with the treated water when doses of disinfectant used in the treatment process did not kill bacteria, viruses and fungi completely [8–10].

The source of pollution in the water pipe network may also be the so-called secondary contamination of water [11]. Hydraulic conditions in the water pipe networks (often oversized network) co-decide about changes in the physiochemical and bacteriological composition of water. The main mechanisms causing secondary pollution of the water pipe network include [2, 8, 9, 12]:

- corrosion and oxidization (susceptibility of the material of the pipes),
- significant changes in speed of flow (sludge is washed out),
- low speed of water (stagnant water in water pipes, increase in temperature of water),
- rapid change in pressure resulting in local vacuum (sludge is washed out),
- poor technical and sanitary condition of pipes (corrosion of pipes, a large quantity of bio-film, pipes leak),
- corrosion caused by aggressive water,
- lack of chemical instability of the water,
- inappropriate water treatment causing its chemical instability,
- high doses of unused disinfectant remain in water (an increase of corrosion),
- accumulation of sludge in the network,
- presence of biochemical processes in the network,
- contamination of the network during repairs, replacement of pipes and fittings (the possibility that pollutants from the ground will pass into water),
- household and industrial devices directly connected to the network (pollution from the installation is sucked into the network.

Water supply tanks should be also considered a source of water pollution in the water pipe networks. It is a possible place where microorganisms can appear due to long residence time of water and so-called dead zones of the tank [13]. In the case of occurrence of contamination, the collective water supply system (CWSS) operator faces a serious task to reduce the spread of contamination, to isolate the most vulnerable areas, to inform about the threat [14].

The aim of this paper was to present the method for determining the risk of the first type and the risk of the second type of water consumers using risk maps.

2. MATERIALS AND METHODS

Safety in WDS is defined as characteristics of a system that shows resistance to dangerous situations (threats) with attention focused on the unreliability of the system safety (vulnerability to the dangerous situation) [3, 8, 13]. The measure of WDSs safety is risk [11, 15]. Nowadays, water pipe companies try to get quality management certificates, according to the international standard ISO9001:2000 that requires the procedures to estimate widely understood risk. According to [15], risk (*r*) is interpreted as a set of the products of probabilities (P) and consequences (C):

$$r = \{P_1C_1, P_2C_2, \ldots, P_nC_n\} \tag{1}$$

Risk assessment is a procedure that consists of [11]:
- hazard identification,
- assessment of the probability of threat occurrence,
- assessment of the vulnerability to threat,
- consequence analysis.

Consumer's risk (individual) r_C is the sum of the first kind risk associated with the possibility of interruptions in water supply, and the second kind risk associated with the consumption of poor quality water [5, 13]. Consumer's risk is a function of the following parameters: probability P or frequency f of undesirable events in water distribution subsystem which are directly felt by water consumers, related losses C (e.g. purchase of bottled water, possible medical expenses after consuming unfit for drinking water or immeasurable losses such as living and economic difficulties and loss of life or health), the degree of vulnerability V to undesirable events [2, 11, 13, 16, 17]. The following formula for determining risk measure to analyse water consumer safety was assumed:

$$r_C = W_{\mathrm{I}} r_{C\mathrm{I}} + W_{\mathrm{II}} r_{C\mathrm{II}} \tag{2}$$

where: W_{I} – weight of risk of the first type, W_{II} – weight of risk of the second type, $r_{C\mathrm{I}}$ – the risk of the first type, $r_{C\mathrm{II}}$ – the risk of the second type.

Two types of risk include two different and independent failure scenarios and different consequences of these scenarios (lack of water supply or contaminated water delivered). Vulnerability parameter (V) takes into consideration occurrence of specific safety barriers in water pipe networks which have an effect on risk level. Proposed method can be used in expanded water main pipe networks and it takes into account previous studies on water pipe networks risk assessment [2, 5, 13, 14].

For the risk of the first type, associated with quantity of supplied water, and for the risk of the second type, associated with quality of supplied water, a three parametric definition was assumed [11]:

$$r_{C\mathrm{I,II}} = P_{i\mathrm{I,II}} C_{j\mathrm{I,II}} V_{k\mathrm{I,II}} \tag{3}$$

where: $P_{i\mathrm{I,II}}$ is the probability of event occurrence that may cause the risk of the first type or the risk of the second type, $C_{j\mathrm{I,II}}$ – losses caused by an undesirable event that may cause the risk of the first type or the risk of the second type, $V_{k\mathrm{I,II}}$ – vulnerability associated with the occurrence of the undesirable event that may cause the risk of the first type or the risk of the second type.

The following point and descriptive scale for the particular risk parameters according to Tables 1–3 was proposed. The criteria presented below were developed based on authors' research and study of literature [2, 3, 11, 14, 17–22].

Table 1

Criteria of point and descriptive scale for the parameter $P_{i\mathrm{I}}$, $i = \{1, 2, 3\}$

Point weight	Description of the parameter *P*	Ranges of probability undesirable event occurrence *P*
1	low probability	once in 5 years
2	medium probability	once in 2 years
3	high probability	once a month and more often

Table 2

Criteria of point and descriptive scale for the parameter $C_{j\mathrm{I}}$, $j = \{1, 2, 3\}$

Point weight	Description of the parameter *C*
1	Small losses: – drop of daily water production ($Q_{d\max}$) up to 70% of the nominal water production (Q_n), or interruptions in water supply up to 2 h – isolated consumers complaints – number of threatened residents ≤500
2	Medium losses: – $Q_{d\max}$ = <30–70)% Q_n or interruptions in water supply up to (2–12] h for individual consumers – drop of water pressure in water–pipe network – financial losses – number of threatened residents – (500–2000].
3	Large losses: – $Q_{d\max}$ < 30% Q_n, drop of water pressure in water–pipe network – failure in mains water supply, interruptions in water supply >24 h for particular housing estates, districts or a whole city – considerable financial and social losses – number of threatened residents >2000

Criteria of the risk of the second type for the probability parameter and vulnerability parameter were assumed in the same way as for the risk of the first type risk (Tables 1, 3).

Table 3

Criteria of point and descriptive scale for the parameter V_{kI}, $k = \{1, 2, 3\}$

Point weight	Description of the parameter *V*
1	Low vulnerability to failure (high resistance): – the network in the closed system, the ability to cut off the damaged section of the network (in order to repair it) – the ability to avoid interruptions in water supply to customers, full monitoring of water–pipe network (continuous measurements of pressure and flow rate at strategic points of the network) covering the entire area of water supply, utilising SCADA and GIS software, the possibility to remote control of network hydraulic parameters – emergency reserve in network water tanks covering the needs of the city for at least 24 h ($Q_{d\max}$ or $Q_{d.\mathrm{avg}}$ – daily average water production) – comprehensive system of emergency warning and response – full use of alternative water sources.
2	Medium vulnerability to failure (medium resistance): – the network in the mixed system, the ability to cut off the damaged section of the network by means of gates (water supply to customers is limited because of the network capacity) – water–pipe network standard monitoring, measurements of pressure and flow rate – delayed emergency response system – alternative water sources do not cover the needs completely
3	High vulnerability to failure (low resistance): – the network in the open system, the inability to cut off the damaged section of the network by means of gates without interrupting water supply to customers – limited water–pipe network monitoring – delayed emergency response system – limited access to alternative water sources

The point and descriptive scale for the parameter C is shown in Table 4. The criteria presented below were developed on the basis of own research and study of literature [1, 9–11].

Table 4

Criteria of point and descriptive scale for the parameter C_{jII}, $j = \{1, 2, 3\}$

Point weight	Description of the parameter *C*
1	2
1	Small threat: – local deterioration of water quality – perceptible organoleptic changes of water (odour, changed colour and turbidity), but minimal threat to further water quality deterioration – complaints of water consumers – lack of threat for consumers health

Table 4 continued

1	2
2	Medium threat: – considerable organoleptic problems (odour, changed colour and turbidity) – numerous complaints – information in local media – threat to consumers health (the normative values for microbiological and/or physiochemical indicators are exceeded, lack of pathogenic microorganisms)
3	Large threat: – secondary water contamination in water–pipe network – possibility that a large group of consumers will be exposed to consume poor quality water – professional emergency services are involved – test results for indicator organisms reveal high levels of toxic substances – information in national media, physiochemical indicators and/or pathogenic microorganisms are exceeded – exposed people need hospitalisation

In this way, possible values of the risk of the first type or the risk of the second type were calculated, according to Eq. (3), the risk takes values in the range [1–27]. The risk matrix is shown in Table 5.

Table 5

The risk matrix

P	*C*		
	1	2	3
	V = 1		
1	1	2	3
2	2	4	6
3	3	6	9
	V = 2		
1	2	4	6
2	4	8	12
3	6	12	18
	V = 3		
1	3	6	9
2	6	12	18
3	9	18	27

Based on the presented risk matrix, a three step scale of risk was proposed:

- tolerable risk [1–8],
- controlled risk (8–12],
- unacceptable risk [18–27].

For the assumed weights ($W_{\mathrm{I}} = 1$ and $W_{\mathrm{II}} = 3$) water consumer's risk was calculated according to Eqs. (2) and (3) is defined as:

- tolerable for $r_C = [4–25]$,
- controlled for $r_C = (25–54]$,
- unacceptable for $r_C = (54–108]$.

3. APPLICATION CASE

3.1. CHARACTERISTICS OF THE WATER DISTRIBUTION SUBSYSTEM

To develop risk maps WDS hydraulic model (EPANET) can be used. The analysed WDS supplies water to about 170 thousand residents. The network operates at 80% in a closed system. Average daily water production is 37 500 m^3. A skeleton of the water pipe network are 4 mains transporting treated water from the second stage pumping station (Fig. 1):

- Mains 0 (∅ 1200, ∅ 1000, ∅ 800 mm) is the largest city mains. It transports water from the water treatment plant (WTP) and supplies the north western part of the city and tanks 1.
- Mains 1 (∅ 400 mm) transports water from WTP to the central and northern parts of the city.
- Mains 2 (∅ 400 mm) transports water from WTP to the southern and central parts of the city.
- Mains 3 (∅ 400 mm) transports water from WTP to the eastern and north-eastern parts of the city, supplying tanks 2.

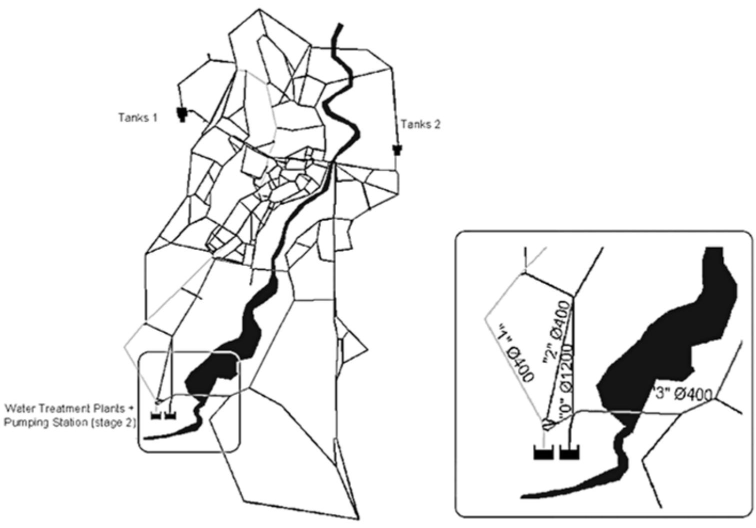

Fig. 1. Diagram of the WDS

3.2. ANALYSIS OF THE RISK OF THE FIRST TYPE

For quantitative analysis of the risk of the first type (threat related to lack of water supply), the failure in mains 0, near the WTP, was selected. Failures in other mains did not cause a drop below the required pressure and these results are not presented in this paper. The hydraulic model of the WDS was used for analysis [16]. In this model we defined:

- for junctions: consumption, ordinates of pressure,
- for segments: length, roughness, diameter,
- volume of tanks,
- operating parameters of the second stage pumping station,
- uneven water consumption throughout the day.

Figure 2 shows the pressure distribution in the water pipe network, obtained by a simulation of the failure in mains 0 (complete closure of the flow for a period of 12 h) near the WTP, carried out using the EPANET 2.0. The paper presents results of analysis of the risk of the first type before and after putting into operation a new water supply tank ($V = 17\ 500\ m^3$) in the complex Tanks 1.

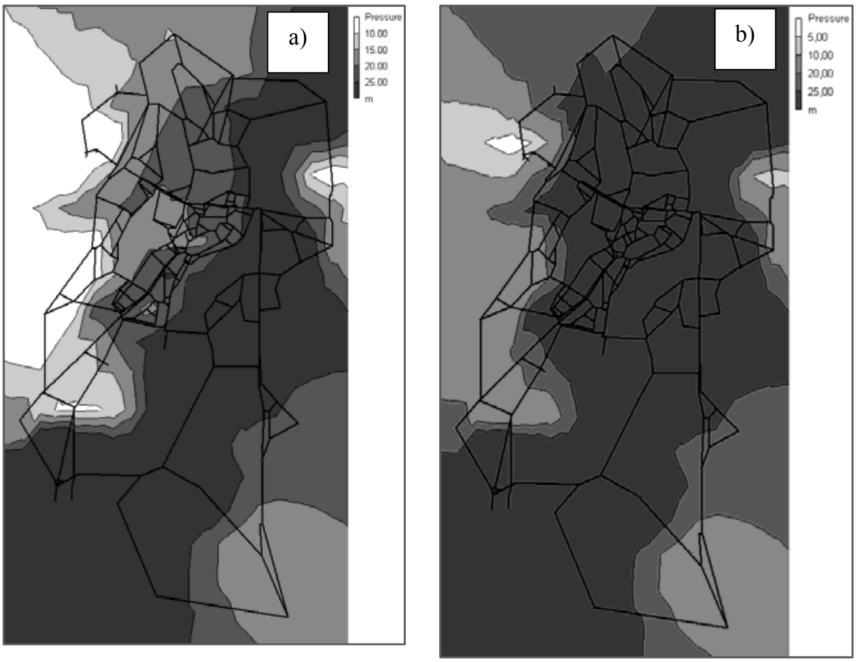

Fig. 2. Distribution of pressure in the WDS (failure of the mains 0): a) before putting into operation a new water supply tank, b) after putting into operation a new water supply tank

Based on the pressure in the network and height of buildings, a number of residents without water was determined (Tables 6, 7). The WDS supply area was divided into zones depending on the average height of buildings:

- high buildings (4 floors) – zones A–P,
- low buildings (up to 2 floors) – zones C, Q, R.

For the parameter C, the number of residents threatened by lack of water supply (RT), the weights were assumed according to Table 2:

- $RT \leq 500$ with the weight 1,
- $500 < RT \leq 2000$ with the weight 2,
- $RT > 2000$ with the weight 3.

Table 6

Number of residents without water supply due to failure of the main 0 – before introducing into operation a new water supply tank and rc_I ($P = 3$, $V = 2$)

Zone	1	2	3	4	C_I	rc_I	
						Value	Level
A	0	3800	500	4300	3	18	unacceptable
B	100	500	0	600	2	12	controlled
C	0	0	0	0	1	6	tolerable
D	0	2150	3150	5300	3	18	unacceptable
E	0	1250	1150	2400	3	18	unacceptable
F	950	50	0	1000	2	12	controlled
G	0	1950	700	2650	3	18	unacceptable
H	200	1350	0	1550	2	12	controlled
I	400	50	0	450	1	6	tolerable
J	400	300	0	700	2	12	controlled
K	0	0	0	0	1	6	tolerable
L	150	900	250	1300	2	12	controlled
M	650	250	0	900	2	12	controlled
N	0	0	0	0	1	6	tolerable
O	0	0	0	0	1	6	tolerable
P	0	0	0	0	1	6	tolerable
Q	0	0	0	0	1	6	tolerable
R	0	0	0	0	1	6	tolerable

1 – number of residents without water supply on the highest floor, 2 – number of residents without water supply on the two highest floors, 3 – number of residents without water supply on the three highest floors. 4 – number of residents without water supply, C_I – point weight for the threatened residents.

The risk measure was calculated based on Eq. (3). The scales for the parameters P were assumed in accordance with Table 1. The worst case was analysed, where the probability of failure of the main is high, with the weight of the parameter $P = 3$. In the analysed CWSS, there is a standard monitoring of water main pipe networks, therefore $V = 2$ (according to Table 3) was assumed. In Table 6, the number of residents without water supply due to failure of the main 0 (before putting into operation a new water supply tank) and rc_{I} are presented.

In Table 7, the number of residents without water supply due to failure of the main 0 (after putting into operation a new water supply tank) and rc_{I} are presented.

Table 7

Number of residents without water supply due to failure of the main 0 after introducing into operation a new water supply tank and rc_{I} ($P = 3$, $V = 2$)

Zone	1	2	3	4	C_{I}	rc_{I}	
						Value	Level
A	0	0	0	0	1	6	tolerable
B	0	0	0	0	1	6	tolerable
C	0	0	0	0	1	6	tolerable
D	0	0	0	0	1	6	tolerable
E	0	0	0	0	1	6	tolerable
F	0	0	0	0	1	6	tolerable
G	400	650	650	1300	2	12	controlled
H	0	0	0	0	1	6	tolerable
I	0	0	0	0	1	6	tolerable
J	0	0	0	0	1	6	tolerable
K	0	0	0	0	1	6	tolerable
L	400	100	600	700	2	12	controlled
M	0	0	0	0	1	6	tolerable
N	0	0	0	0	1	6	tolerable
O	0	0	0	0	1	6	tolerable
P	0	0	0	0	1	6	tolerable
Q	0	0	0	0	1	6	tolerable
R	0	0	0	0	1	6	tolerable

1 – number of residents without water supply on the highest floor, 2 – number of residents without water supply on the two highest floors, 3 – number of residents without water supply on the three highest floors. 4 – number of residents without water supply, C_{I} – point weight for the threatened residents.

The maps of the risk of the first type for the analysed case are shown in Fig. 3. Based on Fig. 3, it was found that before putting into operation a new water supply tank the most vulnerable to the risk of the first type are zones A, D, E, G, and the number of the residents potentially threatened by the risk of the first type is 21 150. After putting into operation a new water supply tank the most vulnerable to the risk of the first type are only zones G, L and the number of the residents potentially threatened by the risk of the first type is 2000. These results demonstrate the validity of the new tank for water supply safety.

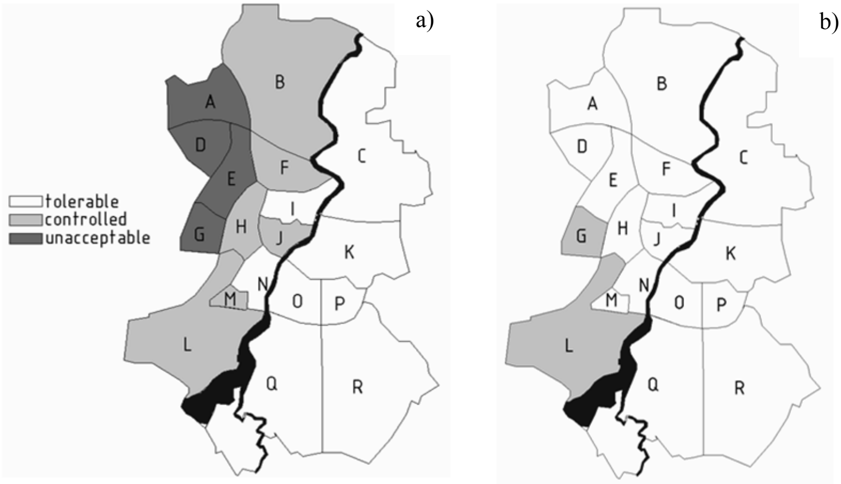

Fig. 3. The map of the risk of the first type: a) before putting into operation a new water supply tank, b) after putting into operation a new water supply tank

3.3. ANALYSIS OF THE RISK OF THE SECOND TYPE

The qualitative analysis of the risk of the second type, associated with delivering poor quality water, due to water contamination in the water pipe network, was carried out using a hydraulic model of the WDS. It was assumed that water pollution threatening

Fig. 4. The time of the spread of contamination in the WDS (contamination appeared at the output of the WTP)

the health and lives of water consumers appeared at the output of the WTP. The average time of the spread of contamination in the WDS is shown in Fig. 4.

The most threatened zones are those near the WTP, having the shortest time of the spread of contamination. It was assumed that the longer time of the spread, the more time there to inform water consumers about the threat is and prepare alternative water supply. Additionally, after some time the concentration of impurities in the WDS decreases. This explains why for the parameter *C* the following three stage scale depending on the average time of the spread of contamination (*AT*) in the WDS, was assumed:

- C_{II} = 1 for *AT* > 24 h (according to Table 4 small threat: lack of threat for consumers health),
- C_{II} = 2 for *AT* = (12–24] h (according to Table 4 medium threat: threat for consumers health, information in local media),
- C_{II} = 3 for *AT* = [0–12] h (according to Table 4 large threat: large group of consumers will be exposed to poor quality water, emergency services involved).

Table 8

Number of residents (*NR*) supplied with poor quality water and rc_{II} ($P = 3$, $V = 2$)

Zone	$NR_{0–12\text{ h}}$	$NR_{12–24\text{ h}}$	$NR_{>24\text{ h}}$	*AT*	C_{II}	rc_{II}	r_{CII} level
A	2150	2700	6000	35	1	6	tolerable
B	600	2300	0	22	2	12	controlled
C	100	1850	2100	36	1	6	tolerable
D	6850	2950	2100	21	2	12	controlled
E	5600	0	0	12	3	18	unacceptable
F	9150	0	0	12	3	18	unacceptable
G	7550	0	0	12	3	18	unacceptable
H	5200	0	0	12	3	18	unacceptable
I	3250	1550	0	16	2	12	controlled
J	3400	200	0	13	2	12	controlled
K	0	400	9250	47	1	6	tolerable
L	5000	0	0	12	3	18	unacceptable
M	5000	0	0	12	3	18	unacceptable
N	8250	0	0	12	3	18	unacceptable
O	0	8600	6900	35	1	6	tolerable
P	0	650	3750	44	1	6	tolerable
Q	4700	2900	0	17	2	12	controlled
R	250	5600	200	24	2	12	controlled

$NR_{0–12\text{ h}}$ – number of residents (contamination reaches them in less than 12 h), $NR_{12–24\text{ h}}$ – number of residents (contamination reaches them in 12–24 h), $NR_{24\text{ h}}$ – number of residents (contamination reaches them in more than 24 h), *AT* – the average weighted time of the spread of contamination in a given zone (weight for *T* = 0–12 h was assumed as 12 h, for *T* = 12–24 h – 24 h, for *T* >24 h – 48 h).

Based on the hydraulic model of the WDS and results shown in Fig. 4, for each zone of the city the number of residents supplied with water of poor quality was determined (Table 8). Residents were divided into three groups with different time of the spread of contamination (see comments below the table). For example, for zone A the average weighted time of the spread of contamination was calculated is:

$$AT_A = \frac{2150 \times 12 + 2700 \times 24 + 6000 \times 48}{2150 + 2700 + 6000} = 35 \text{ h}$$

The risk measure was determined based on Eq. (3). The results of calculations are presented in the form of the map of risk of the second type (Fig. 5).

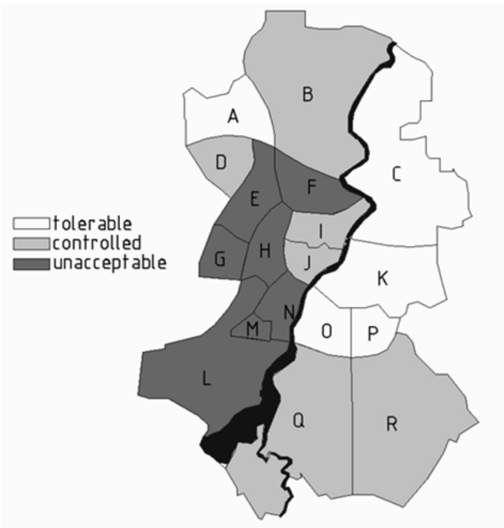

Fig. 5. The map of the risk of the second type

Based on Fig. 5, it was found that the most vulnerable to the risk of the second type are zones E, F, G, H, L, M, N.

3.4. WATER CONSUMER'S RISK

According to Eq. (2), the water consumer's risk was defined as the sum of the risk of the first type and the risk of the second type taking into account the appropriate weights (W_I = 1, W_{II} = 3). For WDS after putting into operation a new water supply tank, the result of the analysis is presented as a water consumer's risk map (Fig. 6).

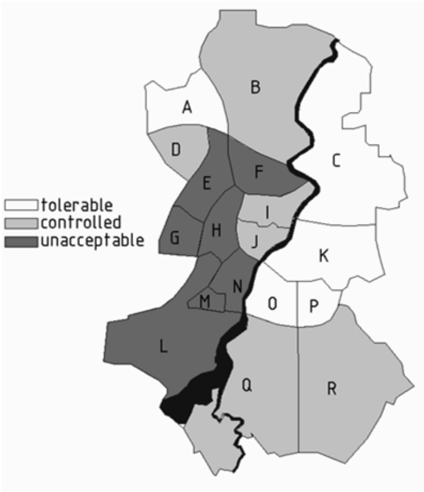

Fig. 6. The map of the water consumer's risk

After putting into operation the tank, consumer's risk has changed to tolerable level in zone A. Risk levels in other zones did not change, because in analysed case, putting into operation a new tank did not affect the time of the spread of contamination in the WDS (contamination appeared at the output of the WTP).

4. CONCLUSIONS

Maps of the risks associated with the operation of WDS (for water consumers safety) should be an important element in emergency of water supply.

The final result of modelling is to present the map of consumer's risk associated with the water pipe networks operation. The presented application example showed the ability to adapt this model to various water pipe networks, with varying degrees of extension. This type of modelling requires:

- a hydraulic model of the water supply network,
- accurate statistics on the failure rate,
- accurate data on the systems preventing the effects of undesirable events.

The developed risk maps allow the identification of the most threatened areas and taking appropriate decisions about modernization to improve safety of water consumers. The model presented in the paper can be used in water supply practice, especially that it is based on the widely used EPANET software.

The monitoring of failure risk of water pipe network is a very important for analyses of functional and technical state of the network, in order to obtain a reliable basis for managing the operation of the network and its modernization.

The presented method allows one to analyse the risk of the first or the second type. It is also possible to analyse so-called consumer's risk using both the risk of the first and second type.

The results of application case demonstrate the validity of the new tank for water supply safety (rc_I). After putting into operation a new water supply tank, consumer's risk mostly depends on the risk of the second type.

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