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WATER NETWORK RISK ASSESSMENT

ESTYMACJA RYZYKA SIECI WODOCIĄGOWEJ

Ryzyko w literaturze technicznej rozumiane jest jako wartość oczekiwana strat, jest więc sumą iloczynu prawdopodobieństwa zdarzeń niepożądanych oraz związanych z nimi strat w rozpatrywanym przedziale czasu. W wielu publikacjach, zarówno krajowych, jak również zagranicznych, przedstawiono wyniki licznych badań z zakresu awaryjności przewodów wodociągowych, zatem można stwierdzić, że prawdopodobieństwo awarii przewodów jest zagadnieniem dobrze rozpoznanym w literaturze naukowo-technicznej. Analizie poddano szereg systemów zaopatrzenia w wodę uzyskując wyniki dla praktycznie pełnego zakresu średnic przewodów, z rozróżnieniem wieku i materiału rurociągów, warunków eksploatacji, czy sezonowości.

Pozostaje wciąż do opracowania zagadnienie strat wynikających z awarii przewodów wodociągowych. Uzyskanie realnych wartości strat wyrażonych w jednostkach monetarnych wydaje się rozwiązaniem optymalnym dla dalszych celów aplikacji w zarządzaniu ryzykiem, jest to jednak problem niezmiernie skomplikowany. Problematykę ryzyka związanego z eksploatacją sieci wodociągowej należy rozpatrywać w dwóch aspektach: ryzyka przedsiębiorstwa świadczącego usługi wodociągowe oraz ryzyka konsumenta wody. Skutkuje to szerokim spektrum strat, zarówno o charakterze finansowym (koszty usuwania awarii, utrata wpływów wynikająca z obniżenia sprzedaży wody, odpowiedzialność cywilna przedsiębiorstw wodociągowych, straty w produkcji itp.) jak również trudniejszych do oszacowania wielkości, np. związanych z obniżeniem komfortu życia czy utratą zdrowia wynikających z niedoboru wody lub jej obniżonej jakości. W efekcie konieczne wydaje się opracowanie uniwersalnych wskaźników strat wynikających z awarii przewodów wodociągowych. Przedmiotem niniejszej pracy jest analiza stosowanych dotychczas wskaźników ryzyka oraz próba przedstawienia nowych wielkości. Zastosowano miary ryzyka zarówno producenta jak również konsumenta wody wynikające z awaryjności przewodów rozdzielczych. Przedstawione wielkości zobrazowano wartościami eksploatacyjnymi ryzyka uzyskanymi dla jednej z dzielnic miasta Krosna uzyskanych podczas badań eksploatacyjnych w ostatnich 5-ciu latach.

1. Introduction

Risk in the technical literature is understood as the expected value of losses, therefore it is the sum of the product of the likelihood of undesirable events and associated with them losses, in the considered time interval [5]:

$$r = \sum_i P_i \cdot C_i \tag{1}$$

where:

P_i – probability of the i-th undesirable event;
C_i – losses associated with the i-th event.

Losses can be referred to both the water producer and water consumers. For losses resulting from the failure of water pipes the following areas of occurrence can be distinguished:

- in relation to waterworks companies:
  - losses resulting from the repair of failure, including the costs of preparing for the repair, its execution, return of segment to service and restoration of the area to its original state,
  - losses associated with the volume of water which was not sold because of the failure - it can be estimated as the average water consumption during the failure,
  - additional losses resulting from the failure, such as the costs of the removal of flooding, changes in traffic organization, etc.,
  - costs arising from the responsibility of waterworks company towards water consumers, for example, penalties for lowering the standards of water supply,
  - costs associated with keeping the maintenance service in readiness,
  - immeasurable losses resulting from the loss of reputation of a waterworks company,
- in relation to water consumers:
  - costs associated with the lack of water supply - for industry and services they are understood as, for example, the value of reduction of production or production of lower quality goods, for housing they are more difficult to estimate, the valuation may be performed by the discretionary methods,
  - costs of the loss of health resulting from difficulties in the maintenance of hygiene,
  - potential costs associated with the inability to use tap water to extinguish fires.

It should be noted that the mentioned methods for assessing the consumers losses, based on the consumers opinions about potential compensations resulting from the disruption of water supply (the Willingness to Accept method), usually give considerably overestimated values, while the Willingness to Pay method, resulting from the potential charges that the consumers would offer to avoid interruptions in water supply, gives much lower values than the Willingness to Accept method and they are usually treated as considerably underestimated [12].

In many publications, both domestic and foreign, the results of numerous studies on water supply pipe failures were presented, therefore it can be concluded that the probability of failure of pipes is a problem well recognized in the scientific and technical literature [17]. Were analysed a number of water supply systems and obtained results for virtually full range of wire diameters, distinguishing between age and pipe material, operating conditions, and seasonality.

The issue of losses resulting from failure of pipes still remains to be developed. Obtaining real values of losses, expressed in monetary units, appears to be the optimal solution for the purpose of further applications in risk management, but this is an extremely complicated problem [7]. Risk issues associated with the operation of water supply should be considered in two aspects: the risk of water supply company and the risk of water consumers. It results in a wide range of losses, both financial losses (cost of failure repair, loss of revenue resulting from the reduction in water sale, water supply company liability, losses of production, etc.) and, more difficult to estimate values, for example, related to the reduction of quality of life or loss of health [6], resulting from lack of water or its poor quality, which can be estimated only on a discretionary basis (e.g. in relation to water consumers the Willingness to Pay method). As a result, it seems necessary to develop new indicators of losses resulting from failure of water pipes, whose estimation would be as simple as possible and at the same time the obtained results would be satisfactorily reliable. Such approach will enable the widespread use of risk in water supply systems management [22].

The subject of this paper is to analyse risk indicators used so far and attempt to present new values. The focus is on consumer's risk arising from the failure of water pipes. The presented values were illustrated by risk operational values obtained for one of the districts of the town of Krosno in last 6 years.

2. Water supply risk indicators

Among a large number of values used to describe losses C the descriptive indicators predominate. The magnitude of both, the probability of failure as well as losses resulting from them, were presented in the form of risk weights and obtaining the risk matrices. These methods have evolved through the introduction of higher number of factors affecting the amount of losses, for example, exposure to threat, the number of people potentially affected by the consequences of failure, the influence of protective barriers preventing the occurrence and consequences of threats and others [13, 18, 24-26, 31].

One of the first value is an expected value of water shortage K_u - the indicator which binds the probability of failure and resulting water shortage. It is determined according to the relation:

$$K_u = 1 - \frac{E(N)}{V_n} \tag{2}$$

where:

- E(N) – expected value of water shortage during the relevant period (m^3);
- V_n – total volume of water needed in the given balancing period, usually calculations are carried out for 1 day, hence V_n is assumed as a nominal daily demand Q_n (m^3).

In practical applications the calculations related mainly to the entire water supply systems rather than individual water pipes, the numerical limit values of this indicator for water supply systems of various sizes, have been developed [33]

Another approach to risk assessment are indexes presented in [23]. The analysis can be performed on one conceptual level, covering the balance of water resources and demand for water (HL0) and on three hierarchical levels from the technical point of view:

- HL1 - includes the subsystems of water intake and water treatment,
- HL2 - includes the subsystems associated with water production and the subsystem of clean water pumping, collecting and transferring,
- HL3 - includes the entire CWSS, including water distribution subsystem.

Indexes determined on the basis of studies made in real conditions concern the system unavailability, the quantity of undelivered water, the number and duration of the undesirable events , as well as the failure to meet water quality parameters.

Figure 1 shows the particular hierarchical levels.

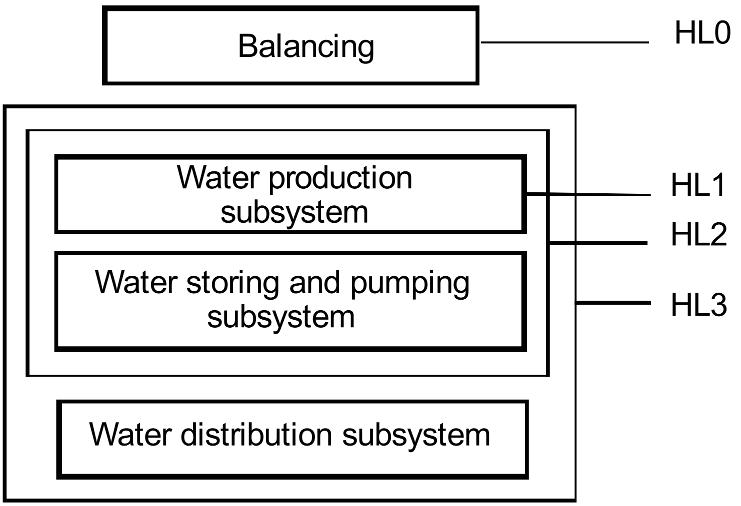

Fig. 1. Decomposition of reliability analysis according to the CWSS hierarchical levels

Rys. 1. Dekompozycja analiz niezawodnościowych według poziomów hierarchicznych SZZW

For the water distribution subsystem they are defined as the probability to meet a specific level of water supply for the amount of water demand or time of water availability for the user, for example, Loss of Water Volume Probability, Expected Water Volume Not Supplied or Loss of Water Shortage Time Expectation [16, 27-28].

The value that can be defined as a measure of risk is time in which the water supply does not meet the requirements of the consumer. This value expresses the time in which the consumer is exposed to the water supply below the acceptable standards, both quantitative and qualitative [1].

The value of indicator is expressed by time (minutes) of exposure of the statistical water consumer per year - Substandard Supply Minutes - SSM [3-4]. SSM is determined from the relation:

$$SSM = \frac{\sum_{i=1}^{n} t_i M_i}{M} \tag{3}$$

where:

t_i – duration of the i-th failure (min);
M_i – a number of residents affected by the i-th failure;
M – a number of residents supplied by the water supply system.

Risk can be also described by indicators used in other industries, for example in energy industry, such as: Average Short Interruption Frequency Index, Average Long Interruption Frequency Index, Average Water Volume Not Supplied, and others.

In the case of water pipes the range of the consequences of failure can be seen as the expected number of customers without water due to failure of the pipe. In this case the risk indicator is the expected number of residents affected by water deficit E(M):

$$E(M) = \sum_i P_i M_i \tag{4}$$

This indicator has some limitations arising from the fact that other groups of water consumers - mainly industry and services - are not taken into account. This disadvantage can be eliminated by expressing losses as the expected number of water connections without water supply E(J), according to the relation:

$$E(J) = \sum_i P_i J_i \tag{5}$$

where:

J_i – a number of water connections affected by the consequences of water pipes failure.

This value does not include the value of water consumed by individual customers and can falsify the obtained results. Therefore, as a negative consequence of failure, the universal value, equal to the demand for water for all groups of receivers, per capita, called further “the equivalent resident”, has been introduced.

$$E(M_E) = \sum_i P_i \frac{Q_{Ni}}{q_{si}} \tag{6}$$

where:

- Q_{Ni} – the expected volume of water not delivered to recipients (m^3);
- q_{si} – is the demand for water for a statistical resident (equal to the average daily demand Q_{da}), ($m^3 \cdot d^{-1}$);
- M_E – the number of equivalent residents serviced by water network.

This indicator allows to differentiate water customers for residential consumers and institutional consumers. Although it does not specify the issue from a financial point of view, however, it clearly evaluates the consequences of pipe failures and at the same time retains the simplicity of estimation, which allows for its widespread usage in risk management [2].

As a basic measure you can use the expected value of losses according to the formula (1), estimating losses in monetary units, but it is believed that taking into account the full spectrum of losses resulting from the failure of pipes is extremely difficult [8].

In this paper the maps of the risk of failures in water distribution pipelines for the district Turaszówka in the town of Krosno, were presented. Risk was shown as the expected value of the equivalent inhabitants - it is an index describing the risk of both the water consumer and the water producer. The risk of the water producer understood as the expected value of financial losses associated with the repair of failure was also shown.

The analysis was based on a model of water supply system developed in the program Epanet 2. The model was created using the data from the Municipal Enterprise for Communal Economy in Krosno, it presents the state of the system at the end of 2008. The data included:

- High pressure pumping stations in Sieniawa, Iskrzynia and Szczepańcowa (pumps characteristics, control algorithms, the ordinates of the axis of the pumps, the arrangement of suction and discharge lines),
- Water reservoirs (dimensions, the ordinates of characteristic filling levels),
- pipes (diameters, material, age, length, the ordinates in the initial and final nodes),
- water intake in the particular segments,
- other elements important for water network operation (pressure reducing valves).

3. The application method

The estimation of risk of water pipes for a district in one of the cities in the south - eastern Poland, was presented. The network diagram with the basic information on pipes is shown in Figure 1. In this segment of the network there are distribution pipes made of PVC and cast iron, with nominal diameters of 100 and 150 mm, connected in rings. Based on the revised pipe network hydraulic model the simulations of the exclusion of the individual pipes from the operation were performed [19]. The analysis shows that in the case of distribution pipes the consequences of failure affect only the customers connected directly to these sections. The exception to this rule are the sections of the network terminal, where, because of the area configuration and the spatial distribution of buildings, the water supply network becomes radial. In the case of the main pipelines, because the city is supplied from 3 sources and water is stored in the network tanks, it can be stated that the closure of the main pipes does not adversely affect the pressure distribution in the water supply network (in the analysed area) until the network tanks are emptied. It means a minimum time of 4 hours, depending on the volume of water demand and filling the tanks [29-30]. Therefore, because the probability of simultaneous failure of one of the analysed distribution pipes and the main pipe is close to 0, only simultaneous exclusion of the individual distribution pipes from the operation, was considered.

The probability of exclusion of pipes was calculated on the basis of operational data from the years 2005-2010. It can be determined using the relationship describing the empirical probability [14-15]:

$$P_i = \frac{T_{pi}}{T_{pi} + T_{ci}} \tag{7}$$

where:

T_{pi} – the average working time without failures (d);
T_{ci} – the average segment closing time during its repair (d).

$$T_{pi} = \frac{1}{\lambda_i l_i} \tag{8}$$

where:

λ_i – failure rate ($d^{-1} \cdot km^{-1}$);
l_i – pipe length (km).

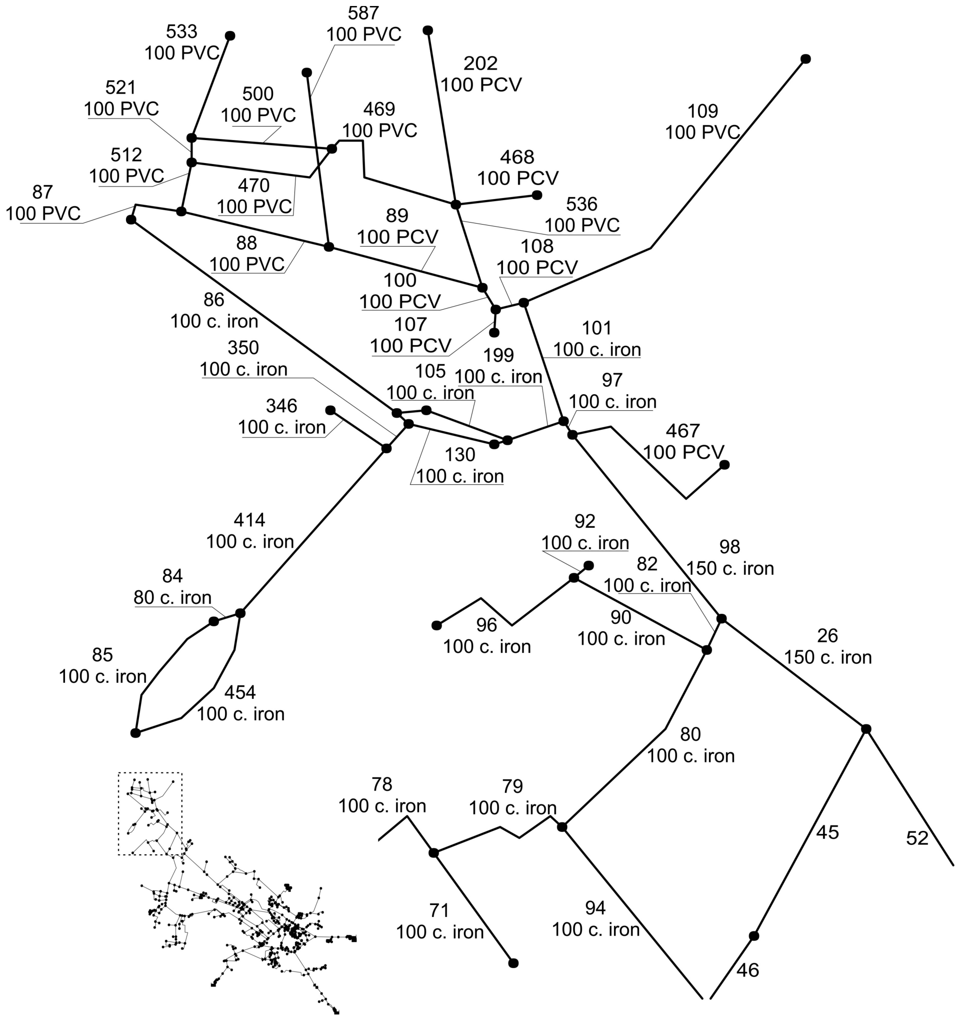

Fig. 1. Diagram of the water network, number of pipeline/nominal diameter/material

Rys. 1. Schemat sieci wodociągowej, numer przewodu/średnica/materiał

The following values were obtained: T_{ci} = 3.96 h for DN 100 mm and 3.76 h for DN 150 mm, for cast iron pipes λ_i = 0.36 $km^{-1} \cdot a^{-1}$, for PVC 0.35 $km^{-1} \cdot a^{-1}$ [20-21]. Risk calculations were based on the formula (6). The results are summarized in Table 1 and shown graphically in Figure 3. The unit water demand for a statistical resident is q_{si} = 276.5 $dm^3 \cdot d^{-1}$.

The value r_i = 0 results from the lack of water partition in the segment (no water pipe connections). The obtained values result from the probability of failure and segmental partition. The compiled values indicate risk, expressed as the expected value of the equivalent residents, in the range 0.00014-0.041. The average risk value for the distribution pipes is 0.0079, and the standard deviation σ = 0.011. Figure 2 shows a graphical picture of the risk of the analysed water network segment. You can notice that for the analysed water network segment there is no dependence between risk and such parameters as age, material or pipe diameter. So we get another tool to manage water supply network.

Tab. 1. Summary of risk calculations for the water network

Tab. 1. Zestawienie obliczeń ryzyka sieci wodociągowej

Pipe no	l_i m	DN_i mm	P_i	$r_i \times 10^4$
202	1270	110	2.0×10^{-4}	468
78	1354	100	2.2×10^{-4}	405
86	873	100	1.4×10^{-5}	330
414	578	100	9.4×10^{-5}	281
79	324	100	5.3×10^{-5}	205
109	759	110	1.2×10^{-4}	106
454	836	100	1.4×10^{-4}	102
467	413	110	6.5×10^{-5}	94
85	760	100	1.2×10^{-4}	93
88	340	110	5.4×10^{-5}	86
94	484	100	7.9×10^{-5}	72
26	276	160	4.1×10^{-5}	65
90	230	100	3.7×10^{-5}	61
587	317	110	5.0×10^{-5}	54
96	562	100	9.1×10^{-5}	46
98	381	160	5.7×10^{-5}	46
71	303	100	4.9×10^{-5}	32
350	40	100	6.5×10^{-6}	25
468	187	100	3.0×10^{-5}	24

Pipe no	l_i m	DN_i mm	P_i	$r_i\times10^4$
500	365	100	5.9×10^{-5}	23
470	413	100	6.7×10^{-5}	22
469	589	100	9.6×10^{-5}	15
533	175	110	2.8×10^{-5}	11
346	137	100	2.2×10^{-5}	9
89	558	110	8.8×10^{-5}	7
100	67	100	1.1×10^{-5}	7
87	107	110	1.7×10^{-5}	5
101	176	100	2.9×10^{-5}	5
92	33	100	5.4×10^{-6}	3
136	24	110	$3.8\times10_{-6}$	1
80	267	100	4.3×10^{-5}	0
82	53	100	8.6×10^{-6}	0
97	32	160	4.8×10^{-6}	0
105	148	110	2.3×10^{-5}	0
107	23	110	3.6×10^{-6}	0
108	25	110	4.0×10^{-6}	0
115	2,5	100	4.1×10^{-7}	0
121	33	110	5.2×10^{-6}	0
130	148	110	2.3×10^{-5}	0
199	112	110	1.8×10^{-5}	0
512	101	110	1.6×10^{-5}	0
521	60	100	9.8×10^{-6}	0

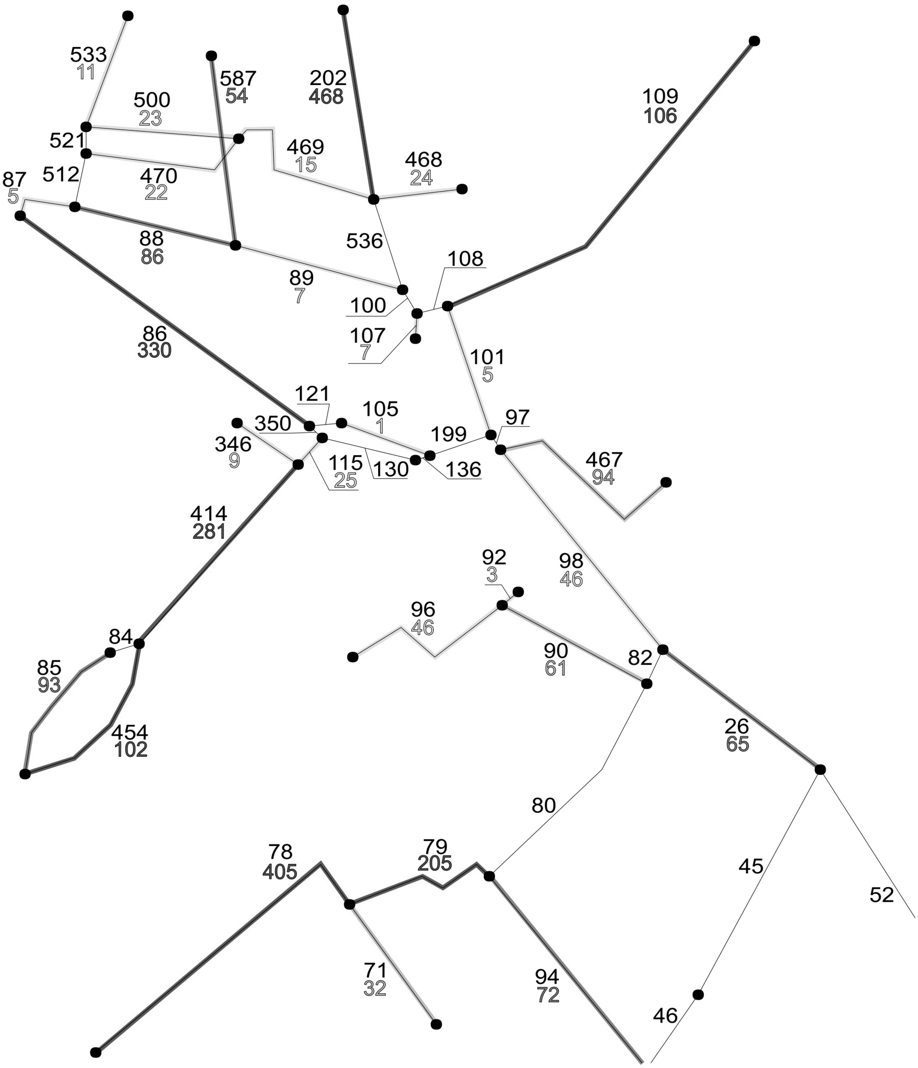

Fig. 2. Map of risk, number of pipeline/r_i×10^4

Rys. 2. Mapa ryzyka, numer przewodu/r_i×10^4

For the water producer the risk characterized in Chapter 1 includes mostly the costs related to the repair of water pipelines. The main components of the cost of water pipelines repairing are shown in [11], for the nominal diameters DN 100-200 mm the structure of costs is the following:

- wages 15.0÷17.2%,
- materials 8.8÷10.6%,
- surface renovation 14.0÷15.5%,

- transport 25.4÷28.8%,
- departmental costs 8.5÷11.5%,
- general expenses 18.2÷19.8% [11].

In the domestic literature the costs of repairs are shown for Wrocław for years 1993-1999 [9-10]. The average unit cost of repairing the pipe joints was 2077 zł for DN 100 and 3115 zł for DN 150 mm, for rupture or perforation repairs the costs amounted to, respectively, 2700 zł and 4985 zł. The obtained values were related to pipes made of iron, the price level - 1999. The prices were updated to the level of 2012, adjusted for inflation, which, according to the CSO (Central Statistical Office) for the years 2000-2011, was 47.9% (the CSO reports). However, the lower degree of urbanization of the analysed area should be noted and therefore the values obtained for Wroclaw were treated as the maximum values. The calculations of risk, based on the formula (1), for the data presented in Table 1, are shown in Table 2. For the city of Rzeszów the approximate cost of the repair of pipes with diameters of 100-200 mm presented in [32] was 1500 zł. The user of water supply system in the town of Krosno estimates the average cost of the repair of failure as 1500 zł. As can be seen from the presented data, the minimum cost of the repair of failure can be estimated as 1500 zł, while the maximum values were 3993 zł for DN 100 mm and 7373 zł for DN 150 mm.

The annual risk associated with the repair costs for water pipes in the Turaszówka district was determined from the definition (1) for the presented above minimum values r_{min}, estimated by the user of the water supply system in Krosno r_{kr} and the maximum values r_{max}, summarized in descending order in Table 2 and shown in Fig 3. It is the water producer risk related to the costs of water supply pipes repairs.

Tab. 2. Summary of producers risk calculations for the water network

Tab. 2. Zestawienie ryzyka producenta w sieci wodociągowej

Pipe no	l_i m	DN_i mm	r_{min} zł/a	r_{kr} zł/a	r_{max} zł/a
78	1354	100	731	1462	1946
202	1270	110	667	1334	1775
86	873	100	471	943	1255
454	836	100	451	903	1202
85	760	100	410	821	1092
109	759	110	398	797	1061
98	381	160	200	400	983
469	589	100	318	636	847
414	578	100	312	624	831
96	562	100	303	607	808
89	558	110	293	586	780
26	276	160	145	290	712
94	484	100	261	523	696
467	413	110	223	446	594

470	413	100	223	446	594
500	365	100	197	394	525
88	340	110	179	357	475
79	324	100	175	350	466
587	317	110	166	333	443
71	303	100	164	327	436
80	267	100	144	288	384
90	230	100	124	248	331
468	187	100	101	202	269
101	176	100	95	190	253
533	175	110	92	184	245
105	148	110	78	155	207
130	148	110	78	155	207
346	137	100	74	148	197
199	112	110	59	118	157
87	107	110	56	112	150
84	104	80	56	112	149
512	101	110	53	106	141
536	99	110	52	104	138
100	67	100	36	72	96
521	60	100	32	65	86
97	32	160	17	34	83
82	53	100	29	57	76
350	40	100	22	43	57
92	33	100	18	36	47
121	33	110	17	35	46
108	25	110	13	26	35
136	24	110	13	25	34
107	23	110	12	24	32
115	2,5	100	1	3	4

The obtained values indicate a considerable spread of risk for particular sections, from 1 zł/a to 1946 zł/a, mainly due to their length and the assumed costs of repairs. The unit risk associated with a failure of 1 m pipe varies in the range from 0.5 zł/m to 2.6 zł/m, depending on the assumed costs of repairs. The mean values of the risk for the section vary in the range from 172 zł/a to 476 zł/a.

You can see some discrepancies in the hierarchy of risk for the individual sections, as exemplified by sections 130 and 199. According to Table 1 the consumer risk is 0 and in Table 2 these sections are in the lower zone of the average risk. It should be noted that a similar hierarchy of risk obtained for the particular sections results from the specific character of water network in the analysed area, resulting from the same type of buildings, similar population density and similar diameters and age of pipes. That is why the risk of water producer and water consumers shows a similar hierarchy of values for individual sections, but one should not generalize this phenomenon. The convergence results from the lack of individual sections supplying different areas of water supply network, as exemplified by section 414, which failure results in shut off of water supply to 84, 85 and 454 supplied by this section. As a consequence the consumer's risk resulting from the failure of this section is more important (it affects higher number of recipients than those who are supplied directly from this section) than the producer's risk which is the expected value of losses related to the repairs of damages.

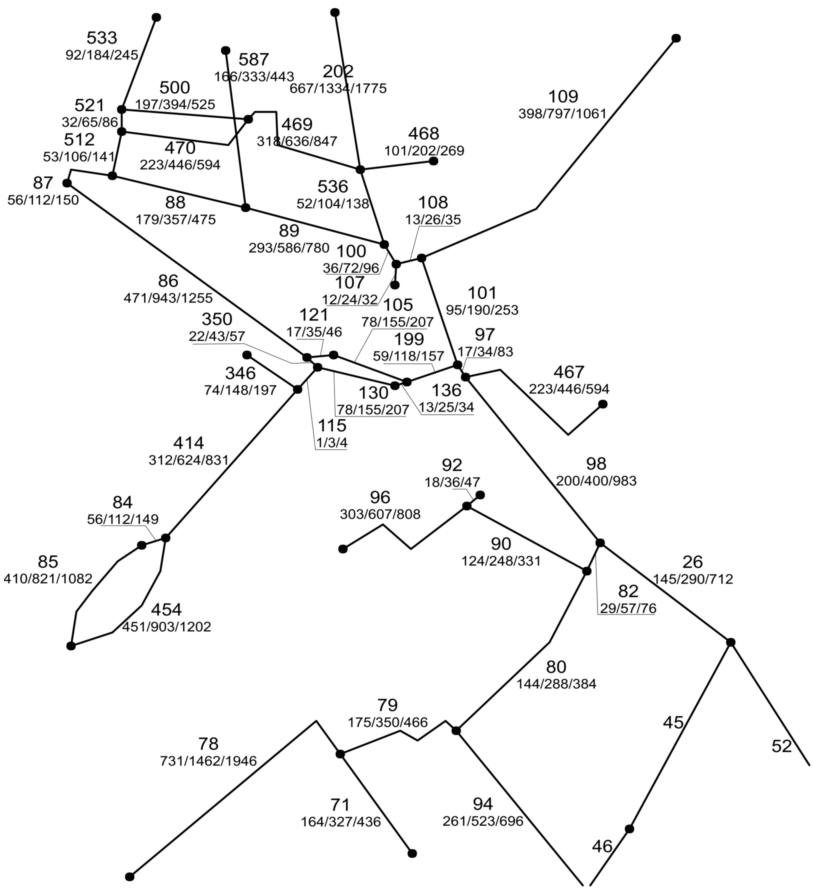

Fig. 3. Map of risk, number of pipeline/r_{min}/r_{kr}/r_{max}

Rys. 3. Mapa ryzyka, numer przewodu/r_{min}/r_{kr}/r_{max}

4. Conclusions

Although the beginnings of the science of risk date back to the 60's of the twentieth century there is still a wide spectrum of issues that require research. The difficulties arising from the global way of describing the risk are particularly pointed out. It is commonly believed that we should aim to develop methods of risk assessment and reliable numerical values of risk, expressed in monetary values. Given the scope of potential losses, such approach is still in research. This also applies to the risk arising from failure of water pipes. Used so far methods and indicators for estimating the risk of failure of water pipes are not very reliable, as a result of taking into account an individual aspect of the losses, or extremely complicated and then they do not find wider application in the waterworks companies management practice. We proposed to express losses resulting from failure of water pipes as the expected value of the number of the equivalent residents without water. It is the value that allows numerical estimation of losses and, especially, the comparison of the consequences of undesirable events - thus it can facilitate decision-making processes in the waterworks company. The presented methodology is also relatively simple and the range of data necessary for risk assessment usually coincides with the values currently used in operational practice. Although this indicator brings us closer to a quantitative description of the risk, however, it is still only a step towards the determination of monetary losses.

Risk identified in this way can be expressed as the expected value of losses resulting from the costs of water pipes repair. For the presented segment of the water supply network in Krosno, on the basis of literature data on the costs of failure, depending on the assumed costs and values describing the given section, the risk varies in the range from 1 zł/a to 2000 zł/a. Risk values for the distribution pipes in the district Turaszówka are from 7 to 21 000 zł per year. One can see a similar hierarchy of risk values for the distribution pipes, it results from the similar failure rate of pipes (similar age, diameter) and evenly spread building density - there is a high correlation between the length of pipes and the number of customers supplied from them.

The presented risk indexes can be used in operational practice of waterworks companies, especially the index of the expected losses associated with the pipe repair costs. Its practical application generally means the possibility to predict the cost of repairs.

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