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FIVE-PARAMETRIC MATRIX TO ESTIMATE THE RISK CONNECTED WITH WATER SUPPLY SYSTEM OPERATION

Risk is a basic category connected with the safety of technical system operation. One of the most often used methods that has a universal character is the so-called matrix of risk which belongs to the quality and quantity methods for risk estimation. The matrix of risk combines the point scale of the probability of an undesirable event occurring with the scales of other parameters that characterise the risk connected with water supply system (WSS) operation. In this paper, we present a short characteristic of the matrix methods allowing the risk associated with WSS operation to be estimated. The five-parametric method has been discussed in detail. In this method, use is made of the probability of an undesirable event P, the scale of losses *S*, a number of endangered people *N*, WSS protection level *O* and the exposure to a danger *E*.

The novelty is the statement that protection *O* is inversely proportional to the size of risk. The more expanded the system of protective barriers, the lesser the risk of threat in WSS. Three levels of risk have been assumed: tolerable, controlled and unacceptable.

1. INTRODUCTION

Risk is a basic category connected with safety. It is derived from the theory of system reliability and safety and connected with the conditions of insignificant, doubtful or questionable effect, with the exposure to danger, loss or harm – the probability that something will bring about the negative result. In such meaning, risk is identified with the loss of safety or, commonly speaking, with the play with danger. The risk connected with the operation of water supply system (WSS) cannot be eliminated because it has many causes. However, it can be reduced to an acceptable level. In Poland, risk as a measure characterising the quality of WSS was introduced by KEMPA [1]. The problems connected with different aspects of risk in water economics are described in monograph [2], and the problems dealing with the nature of risk in WSS operation are presented in the monograph [3]. In WSS operation, the losses caused by the breaks in

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water supply or by low quality of the water supplied are frequently encountered. The related risk will always raise complaints of drinking water consumers. Nowadays the water-pipe companies try to receive quality management certificates according to the international standard ISO9001:2000 that requires the procedures to estimate a widely understood risk.

Today the analyses of risk are commonly used to evaluate the municipal systems. In our country, the act "The environment protection law" passed in 2001 introduced the duty to analyse the risk in the plants of an aggravated or high risk of failure. Therefore the methods for the risk estimation should be developed. The quality and quantity matrix methods seem to be relatively easy to use in WSS. In the case where the analysis shows an unacceptable risk, the preferred course of action is to prevent and counteract the undesirable events and to create the rescue scenario.

2. THE CHARACTERISTIC OF THE MATRIX METHODS FOR RISK ASSESSMENT

2.1. THE TWO-PARAMETRIC RISK MATRIX

From the mathematical point of view, the risk r is inseparably connected with the probability that the undesirable event occurs and with the resulting losses S, which is given by the formula:

$$r = \mathrm{P} \cdot S. \tag{1}$$

In order to assess the level of risk, different calculation techniques are used. One of the most often used methods of an universal character is the so-called matrix of risk that belongs to the quality and quantity methods for risk estimation [5], [7], [8]. The matrix of risk combines the point scale of the probability of an undesirable event occurring with the scale of consequences (losses). Using relation (1) we can obtain numerical values which define the risk. In table 1, the matrix for risk assessment is presented.

Table 1

The matrix of risk

Probability	Consequences		
	Little – 1	Medium – 2	Large – 3
Little – 1	very little – 1	little – 2	medium – 3
Medium – 2	little – 2	medium – 4	large– 6
Strong – 3	medium – 3	strong – 6	very large – 9

According to the basic matrix for risk assessment given above we can analyse different undesirable events assuming the following scale of risk:

- the tolerable risk – a number of points from 1 to 2,
- the controlled risk – a number of points from 3 to 4,
- the unacceptable risk – a number of points from 6 to 9.

The matrix presented above is one of the simplest and can be used for the preliminary risk assessment.

2.2. THE EXAMPLE OF THE EXPANDED THREE-PARAMETRIC MATRIX OF RISK

When we expand the two-parametric matrix by adding the parameter of exposure to threat *E* we, can obtain the three-parametric matrix of risk. The risk can be defined based on numerical indexes. The parameters are as follows: the probability P (frequency) that the threat appears, the magnitude of threat consequences *S* and the exposure to the threat *E*. The exposure to threat should be related to the period of time when a communal water pipe has been used as a source of drinking water. The numerical risk assessment is the product of the above mentioned parameters:

$$r = \mathrm{P} \cdot S \cdot E. \tag{2}$$

The following scales and weights of the particular parameters are assumed:

- The scale of threat probability (frequency) P:
  almost impossible incidents (1 in 100 years); with weight of 0.1,
  occasionally possible incidents (1 in 20 years); with weight of 1.0,
  little probable incidents (1 in 10 years), with weight of 2.0,
  quite probable incidents (once a year), with weight of 5.0,
  very probable incidents (10 times a year), with weight of 10.0.
- The scale of threat consequences magnitude *S*:
  little loss, up to PLN $5 \cdot 10^3$; with weight of 1.0,
  medium loss, PLN $5 \cdot 10^3$–$5 \cdot 10^4$, with weight of 3.0,
  large loss, PLN $5 \cdot 10^4$–10^5; with weight of 7.0,
  very large loss, PLN 10^5–10^6, with weight of 15.0,
  serious disaster, losses over PLN 10^6; with weight of 50.0.
- The scale of exposure to threat *E*:
  slight, once a year or less often, with weight of 0.5,
  minimal, a few times a year; with weight of 1.0,
  occasional, several times a month, with weight of 2.0,
  often, several times a week, with weight of 5.0,
  constant, with weight of 10.0.

The numerical risk assessment carried out in this way takes the values ranging from 0.05 to $5\cdot10^3$. The levels of risk in a five-stage scale are shown in table 2.

Table 2

The levels of risk

Class	Description	Numerical values
1	very slight	$0.05 < r \le 5$
2	slight	$5 < r \le 50$
3	medium	$50 < r \le 200$
4	high	$200 < r \le 400$
5	very high	$400 < r \le 5000$

Very high risk (5) and high risk (4) mean an unacceptable risk. Medium risk level (3) means that some threat occurs but it is not a direct threat. Slight risk level (2) means that the threat without any consequences occurs occasionally. Medium and slight risk should be identified with the controlled risk. When the level of risk is very slight (1) there is no threat and, the risk is tolerable.

2.3. THE FOUR-PARAMETRIC MATRIX FOR RISK [8]

In this matrix, the risk is assessed according to the formula

$$r = \frac{\mathrm{P}\cdot S\cdot N}{O}, \qquad (3)$$

where:

P, S – the point scales as in Section 2.2,

N – the point weight connected with the number of the endangered inhabitants,

O – the point weight connected with WSS protection.

Detailed point scales N and O are given in section 3 of this paper.

3. THE FIVE-PARAMETRIC MATRIX FOR RISK ASSESSMENT

The process of risk assessment allowing us to ensure the safety of WSS operation consists of the following phases:

- determination of a number of inhabitants who use the communal water pipe,
- determination of the representative failure incidents and creation of the scenarios of their development in order to estimate the losses,

• determination of the probability (frequency) that an undesirable incident occurs,
• determination of the exposure time (how often the water pipe is used over a year),
• determination of the risk levels and their division into the tolerable, controllable and unacceptable risk types.

The five-parametric matrix, according to formula (3), for risk assessment has been proposed:

$$r = \frac{\mathrm{P} \cdot S \cdot N \cdot E}{O}, \tag{4}$$

where:

P – the point weight connected with the probability that given representative undesirable event occurs,

S – the point weight connected with the magnitude of losses,

N – the point weight connected with a number of endangered inhabitants,

O – the point weight connected with WSS protection against the extraordinary threats (such protective barriers as: clean water reservoirs, monitoring of early, delayed and late warning),

E – the point weight connected with the exposure to potential threat that is measured by the frequency of a communal network usage.

We should state that WSS protection is inversely proportional to the size of risk. The more expanded the system of protective barriers, the slighter the risk of threat in WSS [4].

This fundamental statement was corroborated by formula (3) as well as by the construction of the risk matrix. The method presented is professional and in such a case, the predefined values of risk assessment are used as the descriptive measures for the parameters in formula (3). Every time the parameters P, *S*, *N*, *O* and *E* are given some level of size according to the following point scale:

• low, $L = 1$,
• medium, $M = 2$,
• high, $H = 3$.

In this way, the point risk scale in the numerical form on the interval of [0.33–81] has been obtained.

The five-parametric risk matrix with the individual numerical values obtained using formula (3) is shown in table 3.

Table 3

The five-parametric risk matrix

N	*E*	P								
		L = 1								
		S								
		L = 1			*M* = 2			*H* = 3		
		O								
		H = 3	*M* = 2	*L* = 1	*H* = 3	*M* = 2	*L* = 1	*H* = 3	*M* = 2	*L* = 1
L = 1	*L* = 1	0.33	0.5	1	0.67	1	2	1	1.5	1
	M = 2	0.67	1	2	1.33	2	4	2	3	2
	H = 3	1	1.5	3	2	3	6	3	4.5	3
M = 2	*L* = 1	0.66	1	2	1.33	2	4	2	3	2
	M = 2	1.33	2	4	2.67	4	8	4	6	4
	H = 3	2	3	6	4	6	12	6	9	6
H = 3	*L* = 1	1	1.5	3	2	3	6	3	4.5	3
	M = 2	2	3	6	4	6	42	6	9	6
	H = 3	3	4.5	9	6	9	48	9	13.5	9
N	*E*	P								
		M = 2								
		S								
		L = 1			*M* = 2			*H* = 3		
		O								
		H = 3	*M* = 2	*L* = 1	*H* = 3	*M* = 2	*L* = 1	*H* = 3	*M* = 2	*L* = 1
L = 1	*L* = 1	0.67	1	2	1.33	2	4	2	3	6
	M = 2	1.33	2	4	2.67	4	8	4	6	12
	H = 3	2	3	6	4	6	12	6	9	18
M = 2	*L* = 1	1.33	2	4	2.67	4	8	4	6	12
	M = 2	2.67	4	8	5.33	8	16	8	12	24
	H = 3	4	6	12	8	12	24	12	18	36
H = 3	*L* = 1	2	3	6	4	6	12	6	9	18
	M = 2	4	6	12	8	12	24	12	18	36
	H = 3	6	9	18	12	18	36	18	27	54
N	*E*	P								
		H = 3								
		S								
		L = 1			*M* = 2			*H* = 3		
		O								
		H = 3	*M* = 2	*L* = 1	*H* = 3	*M* = 2	*L* = 1	*H* = 3	*M* = 2	*L* = 1
L = 1	*L* = 1	1	1.5	3	2	3	6	3	4.5	9
	M = 2	2	3	6	4	6	12	6	9	18
	H = 3	3	4.5	9	6	9	18	9	13.5	27
M = 2	*L* = 1	2	3	6	4	6	12	6	9	18
	M = 2	4	6	12	8	12	24	12	18	36
	H = 3	6	9	18	12	18	36	18	27	54
H = 3	*L* = 1	3	4.5	9	6	9	18	9	13.5	27
	M = 2	6	9	18	12	18	36	18	27	54
	H = 3	9	13.5	27	18	27	54	27	40.5	81

The description of the risk components according to formula (3) is given below:

- The number of endangered inhabitants, *N*:

low – a number of the endangered inhabitants less than 5 000, $N = 1$,
medium – a number of the endangered inhabitants ranges from 5 001 to 50 000, $N = 2$,
high – a number of the endangered inhabitants higher than 50 001, $N = 3$.

- The probability that failure occurs, P:

low – unlikely, once in 10–50 years, P = 1,
medium – quite likely, once in 1–10 years, P = 2,
high – likely, 1–10 times a year or more, P = 3.

- Consequences, *S*:

unimportant – perceptible organoleptic changes of water, isolated consumer complaints, financial losses up to PLN $5 \cdot 10^3$, $S = 1$,

medium – considerable organoleptic changes (smell, significant colour and turbidity), consumer health problems, numerous complaints, information in local media, financial loss up to PLN 10^5, $S = 2$,

severe – endangered people require hospitalisation, professional rescue teams involved, serious toxic effects in test organisms, information in nationwide media, financial loss over PLN 10^5, $S = 3$.

- Protection, *O*:

The questionnaire suggested for the preliminary assessment of WSS protection.

How often is the raw water quality monitored:
every day, 1 point,
periodically (once a month, once a quarter), 5 points,
at random, in case the threat occurs, 10 points.

How often is the treated water monitored:
every day, 1 point,
periodically (once a month, once a quarter), 5 points,
at random, in case the threat occurs, 10 points.

Does the WSS with surface water intake have the protective and warning station:
yes, 1 point,
no, 3 points.

Were the requirements for water intake protective zone implemented:
in full, 1 point,
with some exceptions, 3 points,
some difficulties exist, e.g., economic, legal, etc., 6 points.

Is there any possibility of supplying people with water from an alternative source (emergency wells, two or more water supply sources):
yes, 1 point,
no, 10 points.

Does the water pipe company:
have their own qualified service to eliminate failures in the network, 1 point,

have a signed agreement with the firm that intervenes if necessary, 3 points,
look for the firm to eliminate failure, 10 points.

The emergency volume of the treated water in the water-pipe reservoirs ranges:
from 0% to 10 % $Q_{\max\ d}$, 6 points,
from 10% to 50% $Q_{\max\ d}$, 3 points,
over 50% $Q_{\max\ d}$, 1 point.

If the total number of points equals:
7–10 – high protection level, $O = 3$,
12–34 – medium protection level, $O = 2$,
over 34 – low protection level, $O = 1$.

• Exposure E:
little, a dozen times a year, $E = 1$,
medium, several times a week, $E = 2$,
great, every day (constant), $E = 3$.

The point weight scales should be considered to be proposals for a preliminary risk assessment that can be modified, depending on needs. The advantages of the method presented and the procedure applied lie in the possibility of comparing the risk. In table 4, the risk categories and the corresponding point scales are given. According to the matrix for risk assessment shown in table 3 we can analyse different undesirable events, assuming the risk scale given in table 4.

Table 4

Risk categories

Risk category	Point scale
Tolerable	$0.33 \le r \le 6.0$
Controlled	$8.0 \le r \le 18.0$
Unacceptable	$24 \le r \le 81$

The example of applying the method based on table 3 is the following:
The probability that a given undesirable event occurs $P = M = 2$

↓

Predicted losses are estimated to be $S = M = 2$

↓

The protection level defined based on the supplementary questionnaire $O = H = 3$

↓

The number of endangered inhabitants using water pipe $N = L = 1$

↓

The frequency of exposure is assessed to be $E = H = 3$

The numerical risk value (table 3) *r* = 4.0 which, according to table 4, means a tolerable risk.

4. SUMMARY

- The method for estimating the risk associated with the operation of WSS is based on the assessment of five parameters, i.e., a number of the endangered inhabitants *N*, the probability that the threat occurs P, the magnitude of its negative consequences *S*, protection of WSS against threat *O*, and exposure to threat *E*.
- The five-parametric matrix method for the risk assessment is considered to be innovative because it takes into account the fact that protection (*O*) is inversely proportional to the parameters *N*, P, *S* and *E*.
- The two- and three-parametric matrices can be used for the preliminary risk assessment or for small WSS. The expanded four- and five-parametric matrices should be used by experts analysing the risk connected with water supply in large urban agglomerations.
- Considering the safety of WSS and its stable operation it is very important to categorize the risk levels as follows: tolerable, controllable and unacceptable.

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PIĘCIOPARAMETRYCZNA MATRYCA SZACOWANIA RYZYKA
ZWIĄZANEGO Z FUNKCJONOWANIEM SYSTEMU ZAOPATRZENIA W WODĘ

Ryzyko jest podstawową kategorią związaną z bezpieczeństwem funkcjonowania systemów technicznych. Jedną z najczęściej stosowanych metod o uniwersalnym charakterze jest tzw. matryca ryzyka, która należy do jakościowo-ilościowych metod oceny ryzyka. Matryca ryzyka łączy punktową skalę prawdopodobieństwa wystąpienia zdarzenia niepożądanego ze skalami innych parametrów charakteryzujących ryzyko związane z funkcjonowaniem systemu zaopatrzenia w wodę (SZW). Przedstawiono krótką charakterystykę matrycowych metod szacowania ryzyka w funkcjonowaniu SZW. Szczegółowo omówiono metodę pięcioparametryczną. W skład pięcioparametrycznej matrycy ryzyka wchodzą: prawdopodobieństwo zdarzenia niepożądanego (P), wielkość strat (*S*), liczba mieszkańców zagrożonych (*N*), stopień ochrony SZW (*O*) i czas ekspozycji na zagrożenia (*E*). Zaproponowano następującą formułę szacowania ryzyka:

$$r = \frac{\mathrm{P} \cdot S \cdot N \cdot E}{O}.$$

Nowością jest stwierdzenie, że ochrona (*O*) jest odwrotnie proporcjonalna do wielkości ryzyka. Im bardziej rozbudowany jest system barier ochronnych, tym mniejsze ryzyko wystąpienia zagrożenia SZW. Przyjęto trzy poziomy ryzyka: tolerowane, kontrolowane i nieakceptowalne.