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Characterization of risk function in the analysis and assessment of water supply systems safety

Charakterystyka funkcji ryyzka w analizach i ocenach bezpieczeństwa systemów zaoaptrzenia w wodę

Abstract

Safety is a term referring to lack of threat, guarantee of liquidation or minimizing threats. With regard to drinking water, consumer safety is understood as the probability of avoiding threat resulting from consuming water with quality that is incompatible with applicable normative or lack of water. However, an assumption that the measure of loss of safety is a risk function has become the paradigm. The classical definition of risk implies that it means the possibility of loss, harm with a certain probability. At the same time, there is a term of uncertainty which means lack of certainty and often refers to lack of safety. The main purpose of this paper is to present methods of analysis and risk assessment and the characterization of risk function in probabilistic and fuzzy (possibilistic) aspect.

Keywords: risk, safety, water supply system

Streszczenie

Bezpieczeństwo jest pojęciem odnoszącym się do braku zagrożenia, gwarancji likwidacji lub minimalizacji zagrożeń. W nawiązaniu do konsumentów wody do spożycia rozumiane jest jako prawdopodobieństwo uniknięcia zagrożenia, wynikającego ze spożycia wody o jakości niezgodnej z obowiązującym normatywem lub jej brakiem. Paradygmatem stało się natomiast przyjęcie, że miarą utraty bezpieczeństwa jest funkcja ryzyka. Z klasycznej definicji ryzyka wynika, że oznacza ono możliwość poniesienia straty, szkody z określonym prawdopodobieństwem. Równolegle funkcjonuje termin niepewność, który oznacza brak pewności i często odnosi się do braku bezpieczeństwa. Głównym celem pracy jest przedstawienie metod analizy i oceny ryzyka oraz charakterystyki funkcji ryzyka w aspekcie probabilistycznym i rozmytym (posybilistycznym).

Słowa kluczowe: ryzyko, bezpieczeństwo, system zaopatrzenia w wodę

1. Introduction

Safety is a term referring to lack of threat, guarantee of liquidation or minimizing threats, certainty that nothing bad will happen [1, 2, 5, 9, 11, 12]. With regard to drinking water consumer safety is understood as the probability of avoiding threat resulting from consuming water with quality that is incompatible with applicable normative or lack of water [5]. However, an assumption that the measure of safety loss is the risk function has become the paradigm [5–7, 10, 18]. A holistic approach to the analysis and assessment of the safety of collective water supply systems (CWSS) implies three basic safety control strategies:

- empirical safety control based on the results of statistical research of threats,
- evolutionary safety control based on an individual response to any threat,
- integrated safety control based on risk analysis of possible scenarios of developing dangerous situations.

The PN-ISO 31000 standard "Risk management. Principles and Guidelines" defines risk as a combination of sequences of events and the associated probability of risk occurrence. However, according to the standard ISO 9001: 2015, "Quality management systems" risk is defined as an influence of uncertainty on the functioning of systems or undertakings [16, 12].

In the social sense, risk is associated with threat. At the same time the term uncertainty functions which means lack of certainty and often refers to lack of safety [11, 12]. The decision-making process in terms of ensuring an acceptable level of operational safety for collective water supply systems (CWSS) and thus the effective choice of safety and protection measures for occurring threats is called risk management. At present, for water supply systems the European standards PN-EN 15975-1:2016: Water supply safety – Guidelines for crisis management and risk- Part 1: Crisis management and the PN-EN 15975-2: 2013-12: Water supply safety – Guidelines for crisis management and risk -Part 2: Risk management are applied.

The main purpose of this paper is to present the characteristics of the risk function in probabilistic and fuzzy (possibilistic) aspect.

2. Methods of analysis and risk assessment

Risk analysis is conducted in order to determine risk by estimating the probability of undesirable events and their consequences. The risk analysis should use historical knowledge of the operation of the system, analytical methods and experience. The purpose of risk analysis is to determine its value using the appropriate method [7, 10, 14]. Options of risk analysis approach [7, 17, 16, 18]:

- standard approach – assumes the introduction of standard safety procedures, regardless of the outcome of the risk analysis,
- expert approach – assumes the use of expert knowledge to protect those components of the system that are at high risk, detailed risk analysis – includes risk identification, assessment of threats and their causes, probable consequences and susceptibility to threat, for all the components of the system,

- mixed approach – depending on the complexity of the system one or more of the abovementioned methods is used.

Risk assessment is a comparison of determined values with risk acceptance criteria, which is the basis for safety analysis. At this stage it is very important to set the risk acceptability criteria so that they can be used in the decision making process regarding the operation of the system (e.g. repair or modernization). Such criteria should take into account the reliability requirements of the system (both quantitatively and qualitatively, in accordance with applicable legal regulations, and social and economic conditions) [15, 17, 18].

The risk assessment for CWSS with built-in safety systems requires the use of probabilistic safety assessment (PSA) predictive methods. The PSA modification is a quantitative method for risk analysis (QRA).

The choice of method depends primarily on the purpose of the risk analysis, the level of detail and the size of the data on system operation [6, 7, 9, 16, 19, 20]. Frequently, data are acquired from experts so knowledge of expert systems and in many cases of probabilistic methods is also necessary in risk analysis [8]. Starting risk analysis and assessment, you should know the "nature" of the risk and its basic properties.

Depending on the complexity of the problem, as well as the detailed purpose of risk analysis in the CWSS, the following methods of risk analysis and assessment are used [12–16, 18]:

- probabilistic methods belonging to quantitative methods for risk analysis (QRA) or probabilistic risk analysis (PRA), methods based on mathematical statistics and probability calculus,
- qualitative methods of risk analysis (QLRA),
- quantitative-qualitative methods for risk analysis, including;
  - matrix methods (two or multi-parameter),
  - fault tree analysis (FTA),
  - event tree analysis (ETA),
  - methods using the Markov and semi-Markov processes (Markov risk analysis -MRA),
- possibility methods – possibility risk analysis (PRA);
  - Bayesian methods (Bayes risk analysis – BRA),
  - fuzzy risk analysis (FRA),
  - neuro-fuzzy risk analysis (N-FRA),
- simulation methods using computerized hydraulic models and control, processing and data recording systems (e.g. SCADA), computer databases (e.g. Geographic Information System – GIS), and also the Monte Carlo simulation method, as well as genetic algorithms. They are a tool to support the risk analysis process [16, 18].

The QRA method allows all the significant risk management elements to be taken into account, such as identifying threat sources, determining representative emergency scenarios, estimating the probability of their occurrence, and associated losses and assessing risk based on current criteria.

An important problem is the choice of a risk reduction method that requires introducing some actions to reduce the likelihood of undesirable events (measures that reduce the likelihood of a dangerous event initiating a series of emergency events, measures that reduce the likelihood of developing a dangerous situation into an emergency event) as well as measures reducing consequences.

Criteria for risk acceptability are especially important in defining the objectives of the safety management system in waterworks companies. The level of safety is usually acceptable if the CWSS meets the requirements set out in legal regulations and standards. The decision-making process in terms of ensuring an acceptable safety level for the operation of the CWSS, i.e. the effective choice of safety and protection measures for occurring threats, is called risk management [9–12, 17, 20].

3. Characteristics of the risk function

In risk analysis, priority is given to identifying potential threats and estimating the probable consequences [1, 10, 18]. Analysing the safety of the CWSS, we consider only those threats (undesirable events) that may have the most serious consequences. Those events are most often characterized by small or even very small probabilities of occurrence. Frequently, the lack of a sufficiently large statistical database of such events prevents the value of these probabilities from being correctly determined. In such cases it is necessary to rely on experts' knowledge. It should be borne in mind that in the theory of safety the principle "dealing with all sorts of threats, the ones with the least probability are characterized by the most serious consequences", is applied. You cannot omit unlikely events for which we do not have a database. Another approach, however, is applied in classical systems reliability analyses where all undesirable events (failures) are taken into account to determine the basic reliability characteristics that are a base for planning system modernization and repairs. The value of risk is described by the so-called risk function, representing the dependence of parameters: the probability of occurrence of emergency events posing a threat to the CWSS safety (P), consequences (losses, effects) of emergency (undesirable) event (C), under certain system operating conditions determining the so-called system vulnerability (V) to the development of the so-called representative scenario of emergency events $r = f(P, C, V)$ [4, 10, 15, 18].

The result of the risk analysis should be the expected value of certain losses (e.g. threat for health or lives of water consumers).

From a mathematical point of view, the expected value is determined by the dependence [3, 4]:

- for a continuous random variable:

$$E(C)=\int_0^{\infty} Cp(C)dc \tag{1}$$

- for a discrete variable:

$$E(C)=\sum_{i=1}^{N} c_i \cdot p_i = r(\mathrm{RES}) = r \tag{2}$$

where:

R (RES) $= r$ – risk of a representative emergency scenario,
C – set of possible losses, $C = \{c_i\} = \{c_1, c_2, c_2 \dots n\}$,
i – i-th value of loss or assumed loss range, n – maximum size or loss range.

The probability that the loss C_1 will occur as a result of an undesirable event is:

$$P(C = c_i) = p_i \tag{3}$$

In order to assess the risk acceptability levels (tolerable, controlled, unacceptable), the limit value of losses C_{gr} must be accepted.

Figure 1 shows the risk curve [3, 4] determined by the acceptable level of losses C_1 and the limit level of losses C_2.

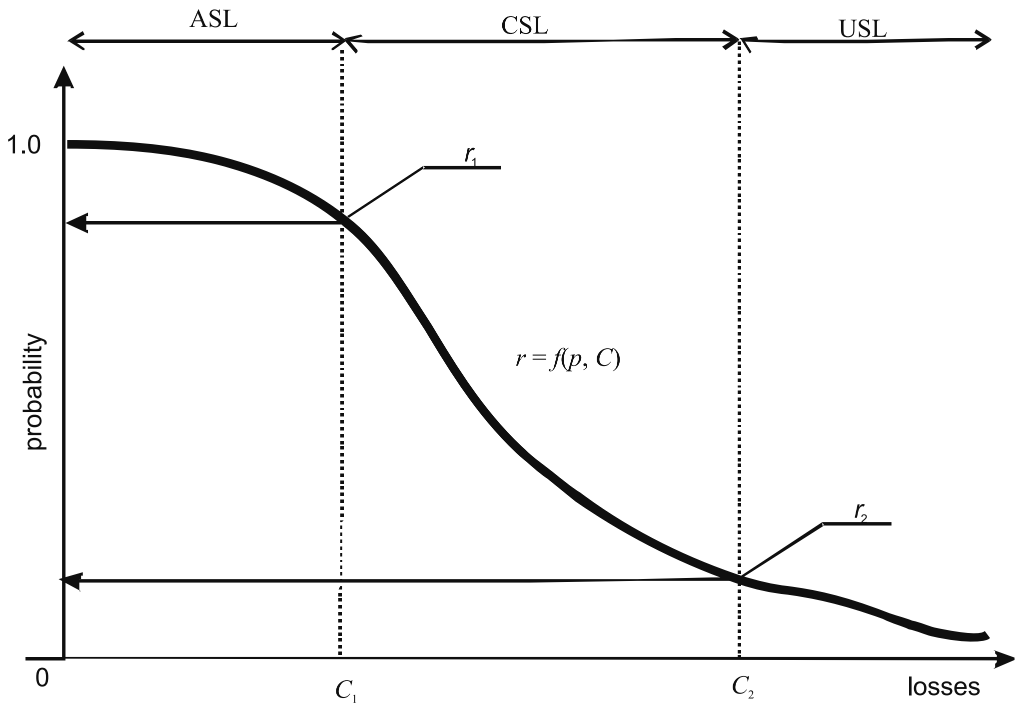

Fig. 1. The risk curve

The characteristic points of the curve are defined as follows:

- r_1 – producer's risk – it is the limit value of risk, under the given operating conditions (determining the vulnerability to threat parameter V), below which there is no real threat to water consumers, the risk is tolerable for water consumers – an acceptable safety level (ASL).
- r_2 – consumer's risk – it is the limit value of the risk, under the given operating conditions (determining the vulnerability to threat parameter V), above which there is a real risk to water consumers, the risk is unacceptable for water consumers – an unacceptable safety level (USL).
- the range from r_1 to r_2 means a controlled risk – a controlled safety level (CSL).

According to the risk curve shown in Figure 1, for the discrete random variable of losses $C = c_i$: the conditional loss expectation value (risk function) in the form [3, 4], is defined:

$$r = E(C|C \leq C_{gr}) = \int_0^{\infty} Cp(C)dc \tag{4}$$

For particular levels of risk the formula (4) takes the form [3, 4]:

- tolerable risk r_T

$$r_T = E(C|(0 < C \leq C_1) = \frac{\int_0^{C_1} C \cdot p(C)dc}{\int_0^{C_1} C \cdot p(C)dc} = \frac{\sum_{i=0}^{C_1} c_i \cdot p_i}{\sum p_i} \tag{5}$$

- controlled risk r_C

$$r_C = E(C|C_1 \leq C \leq C_2) \frac{\int_{C_1}^{C_2} C \cdot p(C)dc}{\int_{C_1}^{C_2} p(C)dc} = \frac{\sum_{C_1}^{C_2} c_i \cdot p_i}{\sum p_i} \tag{6}$$

- unacceptable risk r_U

$$r_U = E(C|C_2 \geq C_2) \frac{\int_{C_2}^{\infty} C \cdot p(C)dc}{\int_{C_2}^{\infty} p(C)dc} = \frac{\sum_{C_2} c_i \cdot p_i}{\sum p_i} \tag{7}$$

In this way, in the risk analysis we can determine the risk values for threats with a predetermined probability. Such an analysis of threats will allow for their hierarchization and proper assessment depending on the aim of risk analysis and assessment. The risk function defined in this way, based on the probability distribution of undesirable events and expected loss values, requires a clear definition of statistical characteristics, which involves the need to have a sufficient amount of reliable data (certainty).When data are burdened with the so-called "high uncertainty", a method that can be useful is fuzzy risk analysis (FRA) [8, 18]. Unlike in the classical set, the fuzzy set boundary is not precisely defined, but there is a smooth transition from a total lack of membership of the element to the set through its partial membership to its total membership. This smooth transition is defined by the so-called membership function μ_R, where R is a set of fuzzy numbers. In this way you can define a fuzzy risk function for which [8, 18]:

- the membership function assigns to each element x from the considered area (space) the value in the interval [0, 1] $\mu_R: X \rightarrow [0, 1]$, which means that every element x from the space X belongs to the fuzzy set R with a certain degree of membership
- the risk fuzzy set R is defined as: $R = \{r_i, \mu_R(r_i)\}$, $i = \{i = T$ – tolerated risk, $i = C$ – controlled risk, $i = U$ – unacceptable risk.
- the values μ_R of the membership function μ_R are real numbers in the interval [0, 1],

The individual risk parameters are described by n linguistic variables (tolerated, controlled, unacceptable). Then fuzzy numbers are assigned to the individual linguistic assessments, which for the triangular membership function are defined as triple $x_j = (l_j, m_j, h_j)$, where: $j = 1, 2, \dots n$.

The values of fuzzy numbers for the triangular membership function assigned to the individual linguistic variables are determined according to the following relations [8, 18]:

- for $j = 1$

$$x_j = \left(0;0;\frac{1}{n-1}\right) \tag{8}$$

- for $2 \le j \le n-1$

$$x_j = \left(\frac{j-2}{n-1};\frac{j-1}{n-1};\frac{j}{n-1}\right) \tag{9}$$

- for $j = n$

$$x_j = \left(\frac{n-2}{n-1};1;1\right) \tag{10}$$

where:

x_j – form of j-th fuzzy number ,
n – number of the linguistic variables describing a given parameter (risk),
j – consecutive number of linguistic variable, $j = 1, 2, \dots n$.

For the linguistic variables that characterize the value of risk in a three-step scale, fuzzy numbers are determined according to the formulas (8), (9), (10), Tab. 1 [18].

Table 1. Fuzzy numbers for the linguistic variables describing risk

The linguistic variables	Fuzzy numbers
tolerated	(0,0; 0,0; 0,5)
controlled	(0,0; 0,5; 1,0)
unacceptable	(0, 5; 1,0; 1,0)

Exemplary fuzzy set of risk $R = \{r_i, \mu_R(r_i)\} = \{(r_T, 0{,}7), (r_K, 0{,}3), \{(r_N, 0{,}0\}$.

4. The application example

An analysis and assessment of the risk of failure for a water supply network for a city with 200 000 inhabitants was carried out. The analysis was performed in the following stages:

- to determine the type of water supply network. It was assumed that from the safety point of view, the analysis should be performed primarily for the main water network,
- to determine the failure intensity indicator based on statistical failure data,
- to determine the limit for the failure intensity indicator for water supply networks,

- to assess the risk of failure by traditional eq. 2.,
- to assess the risk of failure using a fuzzy model (using Matlab Fuzzy Toolbox) [18].

Table 2 presents the basic, statistical characteristics of the failure intensity indicator [18].

Table 2. Basic, statistical characteristics of failure intensity indicator for main water network determined from eight years of operation

Type of water network	Average network length [km]	Average frequency failure	Average failure intensity indicator λ [average frequency failure/km·a]	Standard deviation
main	49.5	13.1	0.26	0.05

Criteria for assessing the value of failure intensity indicator were based on [18]. For main networks, it is assumed that:

- low for $\lambda \leq 0.3$ [average frequency failure/km·a],
- medium for $\lambda = 0.3 \div 0.7$ [average frequency failure/km·a],
- high for $\lambda > 0.7$ [average frequency failure/km·a].

Based on these criteria, the analysed main water network has a low average intensity of failure throughout the year. The criteria for the loss parameter C were adopted in accordance with the principle that for a main network the potential value of losses due to a failure is high. According to formula (4) and curve 1, the value of expected loss $E(C)$ and risk value for the example was estimated as the tolerated risk. In order to verify the conducted analysis, a fuzzy risk analysis was also carried out. The input parameters for the developed model are [18]:

- x_1 – a variable characterizing the probability of occurring an adverse event (failure),
- x_2 – a variable characterizing losses incurred as a result of an adverse event (failure).

The output parameter is the risk value.

The fuzzy risk model is based on Mamdani's inference [18]. The general form of the rules is as follows: *If* x_1 *is* P_i *and* x_2 *is* C_j, *then* $y = r_{ij}$.

Modelling was performed using the Matlab (Fuzzy Toolbox) program. A detailed description of the model can be found in [18]. The probability values of failure occurrence are presented as a data set, whose components are fuzzy subsets described with linguistic variables: $P = \{P_1, P_2, P_3, P_4, P_5\}$. These variables are presented using the adopted triangular membership functions [18]. The values for the loss parameter are also shown as set ($j = 1, 2, 3, 4, 5$), whose elements are fuzzy subsets described using linguistic variables ($C = \{C_1, C_2, C_3, C_4, C_5\}$). These variables are presented by means of the adopted triangular membership functions [18]. Data entered for the analysed example for fuzzy risk assessment (Table 1) showed that the risk is at the controlled level.

5. Conclusions

- Ensuring safe use of public water supply requires the use of management methods that include risk analysis and assessment;
- It includes an assessment of the relationship between occurring threats and used safety and protection barriers;
- Comparison of the risk acceptance criteria should normally be made in the context of "the best judgement" from risk analysis not in the context of optimistic or pessimistic results of analysis;
- A risk assessment also depends on the knowledge and information available to the expert and the decision maker, hence the assessment of the uncertainty in the results will vary depending on the assessment of the people involved in it;
- The risk acceptance criteria should be updated as the knowledge about risk changes;
- Fuzzy risk modelling can be applied to an uncertain database;
- The safety of the CWSS should be considered from the perspective of the whole system, its impact on the environment and not from the perspective of the selected sub-systems or objects;
- A holistic safety management should be built into the system through constant analysis throughout its life cycle.

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