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The Risk As a Measure of System Safety

Water supply system (WSS) is characterized by its continuous work and requires high reliability level for its operating as well as for its safety System operating is inseparably connected with the possibility that different failures (undesirable events) occur. The most often they have random character and then they can be described by the classical methods used in the reliability engineering including the probabilistic methods but sometimes they are the consequences of the events which can cause the catastrophic situation. Events of this type cause the so called domino effect that is a chain of the undesirable events which very often develops according to some definite scenarios. In many cases the consequences of such events can be very serious for water consumers as well as for water pipe companies. The basic measure describing WSS safety is risk and the elaboration of the model to analyze risk connected with WSS will allow to use the safety barriers properly. The paper presents paradigms of risk analysis in WSS in the aspect of improving safety for water consumers.

Keywords: safety, risk, water supply system

1. Introduction

Modern municipal systems operating in urban agglomerations are subject to various types of risk. The extraordinary threat, this is every unexpected event or situation which appears suddenly, has the possibility to develop unfavourably into the domino effect, which threatens people's health and lives or the loss of property [1,2]. Such threats require immediate counteraction, with the aid of the available forces and means. The constant threats, these are the events or situations which appear in a constant or cyclic way in some time intervals. Water supply system (WSS) is characterized by its continuous work and requires high reliability level for its operating as well as for its safety [2,3,4]. System operating is inseparably connected with the possibility that different failures

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(undesirable events) occur [5,6]. The most often they have random character and then they can be described by the classical methods used in the reliability engineering including the probabilistic methods but sometimes they are the consequences of the events which can cause the catastrophic situation. Events of this type cause the so called domino effect that is a chain of the undesirable events [3,7] which very often develops according to some definite scenarios. In many cases the consequences of such events can be very serious for water consumers as well as for water pipe companies. Both kinds of threats (extraordinary and constant) have their sources, mainly, in the action of forces of nature, the lack of the development in technological processes, technological failures or human (system operator) errors. The latter are often followed by technological failures and are connected with the lack of knowledge, imagination, abilities or badly performed technological procedures. Modern civilization progress created new kinds of threats connected with system management computerization, terrorist attacks, psychopath action or ordinary vandalism. Organised actions for the benefit of people safety finalizes in safety management systems. Such systems include national administrative divisions, such as: cities, villages, districts, provinces, and their aim is to assess threats and their distribution, as well as risk connected with those threats in the given territory. The elements of safety system are: creation of maps of threats and risk, modelling of their territorial distribution [3,7].

Since this system belongs to the so called critical infrastructure of cities, it should be constantly watched both for functional as well as security reasons [1,3,5,6,8,9,10]:

- Reliability of the WSS is the ability to supply a constant flow of water for various groups of consumers, with a specific quality and specific pressure, according to the users requirements in the specific operational conditions, at any time (then we use the stationary availability rate K) or in the specific time range (then we use reliability function R(t)) with the acceptable price.
- Unreliability of the WSS can be measured by the probability, frequency and duration of the undesirable events.
- Safety of the WSS means the ability to execute its functions despite of the fact that incidental undesirable events occur.

Risk identification generally means an analysis of risk factors, their sources, determination of the so called vulnerabilities and consequences (effects) of their occurrence [6,10]. Most often this analysis concerns the undesirable events, which can occur in the WSS with certain probability "P" and cause certain losses "C", which may result in the loss of the safety of water consumers [8,9]. These events may be single incidental (e.g., failures in main water pipelines), it may be a series of events or a single event triggering the next series (the so-called domino effect, e.g. pollution of water sources, droughts, floods), which consequently may result in a crisis situation [7,9,10,11,12,13,14].

2. The risk paradigms

Risk assessment is a process consisting of a number of the systematic steps, in which the study of different kinds of threats connected with the WSS operating is carried out [6,9]. The basic purpose of this kind of activities is to collect the information necessary to estimate the safety of the system. Risk assessment should contain [2,5,6,7,9,10]:

- establishment of a ranking of the undesirable events,
- determination of the level (value) of risk,
- proposal of the activities aiming at risk minimization,
- establishment of the time after which the risk can obtain its critical value as a result of different processes, eg. materials ageing.

In the process of risk assessment in the WSS one should take into account the information concerning [6]:

- system operating (exploitation) conditions,
- data regarding the operation of the particular system elements and the dependence between them,
- data concerning energy supply,
- data regarding the possible failures in the system,
- distinction of the states of operating and the states of failure in the system,
- information concerning the causes of failures,
- data regarding the possible consequences of the undesirable events.

Risk assessment includes the so called risk analysis, which is the process aiming at the determination of the consequences of the failures (undesirable events) in the WSS, their extend, sources of their occurrence and the assessment of the risk levels [1,6].

The analysis of the causes of the occurrence of the undesirable events in the WSS can be performed by means of different methods [4,5,6], one of which is the method called Root Cause Analysis (RCA), which requires five answers to the question why? The essence of this method is shown in figure 1, on the example of the analysis of the causes of the repeated failures in a certain section of the water-pipe network [10].

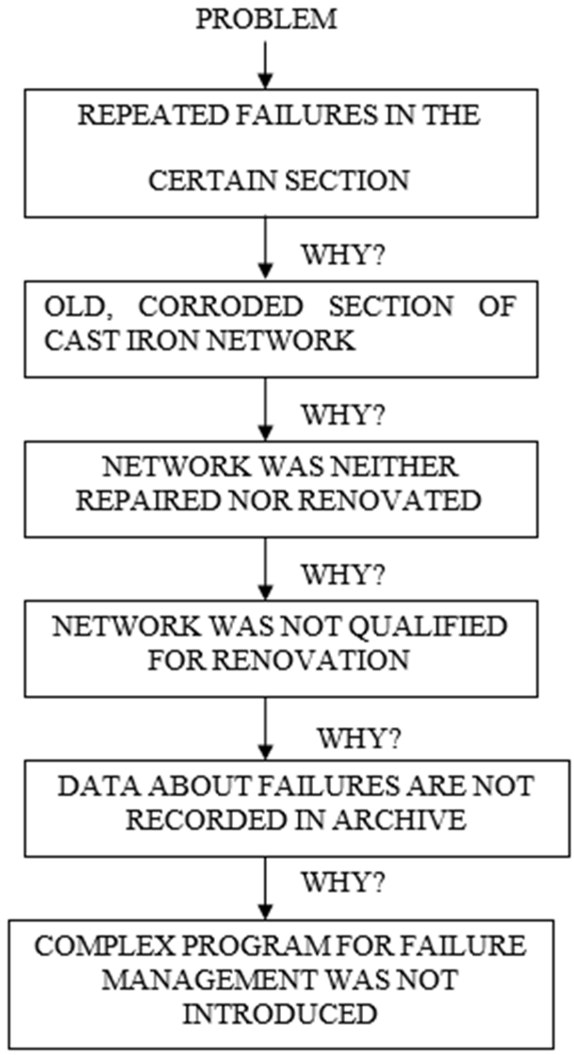

Fig. 1. Example of an identification of causes of the failure in the technical systems (acc. to [10])

In this case the criteria of dividing are: a source of risk, a magnitude of its influence and a scale of its consequences. The individual risk causes the individual losses (a failure in the service water pipes for a given estate). The group risk has an impact on the whole communities (the lack of water supply to the city as a result of the lack of electricity caused by the atmospheric discharge) [15].

It is assumed that the group losses equal the sum of the adequate individual losses. Summation, however, should be performed separately for each category of losses (eg. working loss, loss of health, casualties).

If the risk concerns the individual person, we deal with the individual risk, when it concerns the group of people (community), we call it the group risk [15]. The group risk can be calculated from the formula [15]:

$$r_g = \frac{E(C)}{\Delta t} \tag{1}$$

where:
Δt – time of exposure,
E(C) – an expected value of losses.

The individual risk when the number of people in the hazardous area is m is described by the formula [15]:

$$r_i = \frac{E(C)}{m \cdot \Delta t} \tag{2}$$

3. Risk connected with water supply system operating

The failures of the WSS which occur most often are the following [2,3,6,8,9,10,11,16,17]:

- incidental contamination of water intakes, eg. chemical, biological contamination,
- failures in Water Treatment Stations (WTS), eg. disturbances in the technological process of water treatment,
- failures in transit, main and distributional pipelines, which can be a reason for the secondary water contamination in water-pipe network, as well as breaks or lack of water supply to the receivers, or the drop of water pressure in the network,
- deterioration in water quality in water-pipe network as a result of unfavourable hydraulic conditions (low speed of water flow, pipelines technical conditions),
- failures in power supply, which can cause the lack of the possibility to operate the particular subsystems and elements of the WSS and even the whole system.

The main causes of the above-mentioned incidents are the following [6]:

- actions of the forces of nature,
- deliberate or incidental actions of the third party,
- defects in materials,
- industrial and building catastrophes,
- influence of ground and water environment, including changes of temperature,
- lack of the modernization of the WSS (eg. pipelines renovation, introduction of monitoring and supervision systems),
- errors made by a man (system operator).

Consequences, losses (C) connected with the occurrence of the undesirable events in the WSS can be divided into [6,10,14]:

- Financial consequences (FC) born by the waterworks, connected with the breaks or lack of water supply, costs of restoration of the WSS to its correct operation (failure repair, network disinfection, compensations), etc.
- Social consequences, hygienic and sanitary (SC), the possibility of the loss of health or the lives of water consumers, hygienic and sanitary inconveniences, environmental losses.

The results of studies within the framework of the psychological decision theory show that the perception of risk by a person is a resultant of cognitive, personality and emotional factors.

Risk assessment depends also on a type of risk with which a person is dealing. It is certified that an activity in financial market causes other emotions than activity connected with the threat to health or life.

Quality studies of risk perception allowed to establish some rules in this domain [1,2,4,9]:

- Risk assessment depends on a level of man's experience in dealing with given undesirable event. If this person has never made given operation it is much more difficult for him to perform it, in comparison with a situation when he is well acquainted with a procedure or this procedure even became a routine.
- Man's knowledge about negative consequences of undesirable events influences risk assessment. If somebody has relevant information he is more active in searching and is more sensitive to the symptoms of dangerous situation, in order to avoid making mistake and undesirable event.
- Risk assessment is influenced by a magnitude of negative consequences. The bigger they are the higher risk is assigned to activities potentially connected with it. Man identifies himself with the most unfavourable scenarios. Because of it, in risk analyses and evaluations made by the experts, the number of harmed people (loss of health, death), decrease of life expectancy etc, are given.
- Man considerably overestimates risk of imposed actions and underestimates risk of voluntary actions.
- Man underestimates threats whose negative consequences can appear in a distant, difficult to foresee future.
- Risk has a catastrophic or chronic character. Man is sensitive to a catastrophic risk, but, as studies show, in the long term a chronic risk is bigger, which is underestimated.
- The possibility to implement corrective actions lowers the level of subjective perception of risk.
- The level of fear has a significant influence on a size of perceptible risk.

4. The three parametric risk matrix

Taking into account that WSS is a complex technical system built from subsystems and elements that are firmly interconnected it makes sense to expand the WSS operating risk matrix by next parameters influencing risk size. The three parametric matrix for risk assessment is proposed. The parameters are following: the frequency of the threat occurrence probability (P), threat consequences (C) and the exposure to threat (E) [5,17].

The exposure to threat should be related to the period of time when the public water pipe has been used as a source of drinking water. The numerical risk assessment is a product of the above mentioned parameters [5,17]:

$$r = P \cdot C \cdot E \tag{3}$$

The following scales and weights of the particular parameters are assumed [1,5,17]:

- scale of threat frequency (P) [4,17]:
  - almost impossible incidents (1 in 100 years); with weight 0.1;
  - occasionally possible incidents (1 in 25 years); with weigh 1.0;
  - little probable incidents (1 in 5 years), with weigh 2.0;
  - quite probable incidents (once a year), with weigh 5.0;
  - very probable incidents (10 times a year), with weigh 10.0;
- scale of threat consequences size (C) [17]:
  - little loss up to 2·104 EUR ; with weight 1.0;
  - medium loss from 2·104 to 2·105 EUR, with weight 3.0;
  - large loss 2·105 EUR – 106 EUR; with weight 7.0;
  - very large loss 106 – 107 EUR, with weight 15.0;
  - serious disaster, losses over 107 EUR; with weight 50.0;
- scale of exposure to threat (E):
  - slight, once a year or less often, with weight 0.5;
  - minimal, a few times a year; with weight 1.0;
  - occasionally, several times a month, with weight 3.0;
  - often, several times a week, with weight 6.0;
  - constant, with weight 10.0;

The numerical risk assessment determined in this way takes the values within the range 0.05 to $5 \cdot 10^3$. The levels of risk in the five stage scale are shown in table 1 [1,17].

Table 1. The levels of risk

Risk values	Risk level
0,05 < r ≤ 9	tolerable
9 < r ≤ 60 60 < r ≤ 250 250 < r ≤ 450	controlled
450 < r ≤ 5000	unacceptable

The risk assessment is made according to the second formula [1,5,17]

$$r = P \cdot C \cdot S \tag{4}$$

where:
P – point weight connected with the probability that the representative undesirable event occurs, from 1 to 5,
C – point weight connected with the magnitude of losses, from 1 to 5,
S – point weight connected with the public feelings, from 1 to 3.

Point scales for the particular components of the risk measures are shown below Fig. 2. [1].

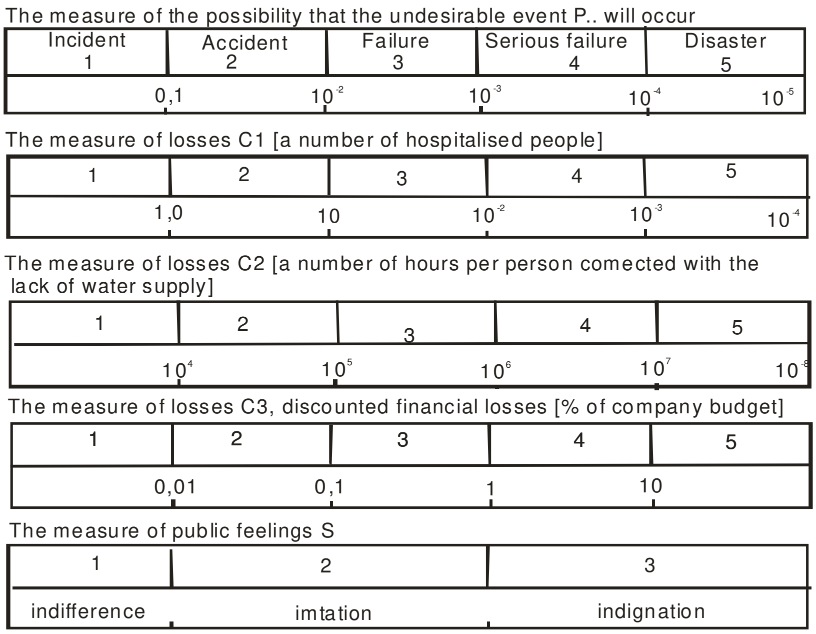

Fig. 2. Point scales for the particular components of the risk measures (according [1])

The finely weight of the magnitude of losses is made according to the formula [1]:

$$C = \frac{C_1 + C_2 + C_3}{3} \tag{5}$$

Point scale to measure risk is within the range 1 to 75. The following risk levels are assumed: r = 1 ÷ 12 – the tolerable risk, r = 15 ÷ 36 – the controlled risk, r = 40 ÷ 75 – the unacceptable risk [1].

5. The example of risk assessment

The failure scenario is the following [1,5,18]:

- there is a microbiological contamination, Clostridium perfringens, in the section of surface water intake,
- technological process of water treatment and disinfection do not guarantee that this kind of contamination will be removed,
- early warning monitoring did not detect this threat,
- in the water pipe network the existence of the bacteria has been detected in the late warning monitoring,
- state of emergency lasted for almost 98 hours,
- there are 50 000 inhabitants in the town, 40 000 of whom use municipal water-pipe.

The experts assessed the measures of risk connected with such threat in the following way:

- the probability that such failure scenario will take place is $P = 10^{-3}$, which means the category of a serious failure, P = 3,
- about 90 people had to be hospitalised, $C_1 = 3$,
- a number of hours per person connected with the lack of water in public water-pipe is: $45\,000 \cdot (3 \cdot 24 + 8) = 3{,}6 \cdot 10^6$, $C_2 = 4$,
- limited use of municipal water and the discounted direct and indirect financial losses resulting from threat (drop in sale of municipal water, compensation payments, 19 % discount in price for water used per month, insurance, lawsuits, drop of confidence in municipal water quality), is 0.65 % of annual waterworks budget, $C_3 = 3$.

According to the formula (5) the point weight connected with the particular losses C_i is:

- $C = \frac{3+4+3}{3} = 3{,}33$, averaging point weight for losses, C = 3, was assumed.
- uncoordinated information policy causes the indignation of public opinion in the town, S=3,

According to the formula (4) risk amounts to r = 3·3·3 = 27 which means the controlled risk. In such case it is necessary to develop the protective barriers, e.g.:

- to increase the effectiveness of sewage management system above water intake,
- to introduce the ozonization process in water treatment technological system,
- to introduce a new, people friendly system of information and dialogue.

6. Conclusions

- Water supply system can be counted among the so called critical infrastructure of state, regions and cities and has a direct influence on the quality of water consumers' life During its operation the system should be continuously controlled, by means of different monitoring systems, in order to protect water consumers from the consequences of its unreliability.
- The objective reality in WSS operating are different types of undesirable events which cause the deterioration of water quality (final product) and lower the level of reliability for water provided by public water pipe, and sometimes have a significant impact on water consumers safety.
- Water supply systems operate in a continuous way for a long period of time. In this connection subsystems and elements that build it also operate intensively. The damage of an element usually involves the necessity to eliminate it from the system, in order to repair the failure. That is why the right identification of state of the particular elements, subsystems and the WSS as a whole, is so important. It is especially important in the process of decision making by a system operator.
- The most effective and advanced method that can be used nowadays in design analyses which aiming at ensuring the reliable and safe drinking water supply from municipal water-pipe, is the risk cadastre. It uses new information technologies to analyse and assess risk connected with water supply to urban population.

References

[1] Rak J.: Podstawy bezpieczeństwa systemów zaopatrzenia w wodę. PAN, Komitet Inżynierii Środowiska, 28, Lublin 2005.

[2] Rak J.: Bezpieczna woda wodociągowa. Zarządzanie ryzykiem w systemie zaopatrzenia w wodę. Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 2009.

[3] Rak J.: Selected problems of water supply safety Environment Protection Engineering Oficyna Wydawnicza Politechniki Wrocławskiej. Wrocław 35, 2, 2009, pp. 23–28.

[4] Rak J., Tchórzewska-Cieślak B.: Czynniki ryzyka w eksploatacji systemów zaopatrzenia w wodę. Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 2007.

[5] Rak J., Tchórzewska-Cieślak B.: Ryzyko w eksploatacji systemów zbiorowego zaopatrzenia w wodę. Wydawnictwo Seidel Przywecki 2013, pp. 1–164.

[6] Tchórzewska-Cieślak B.: Metody analizy i oceny ryzyka awarii podsystemu dystrybucji wody. Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 2011.

[7] Rak J.Bezpieczeństwo systemów zaopatrzenia w wodę. Instytut Badań Systemowych PAN, Warszawa 2009.

[8] Haimes Y.Y.: On the complex definition of risk: a systems-based approach. Risk Analysis, 29(12), 2009, pp. 1647–1654.

[9] Rak J.: Istota ryzyka w funkcjonowaniu systemu zaopatrzenia w wodę. Oficyna Wydawnicza Politechniki Rzeszowskiej, Rzeszów 2004.

[10] Tchórzewska-Cieślak B.: Method of assessing of risk of failure in water supply system. European safety and reliability conference (ESREL), Risk, reliability and societal safety, Taylor & Francis, 2, 2007, pp. 1535–1539.

[11] Hastak H., Baim E.: Risk factors affecting management and maintenance cost of urban infrastructure. Journal of Infrastructure Systems, ASCE, 7(2), 2001, pp. 67–75.

[12] Tchórzewska-Cieślak B., Boryczko K., Rak J.: Analysis of risk and failure scenarios in water supply system. Konferencja: International Water Association World Congress on Water, Climate and Energy, Dublin, Ireland 2012.

[13] Tchórzewska-Cieślak B., Rak J., Piegdoń I.: Risk analysis of water supply interruptions in collective water supply systems. Journal of Polish Safety and Reliability Association, Summer Safety and Reliability Seminars 2(3),2012, pp. 201–207.

[14] Tchórzewska-Cieślak B., Rak J., Pietrucha-Urbanik K.: Safety analysis and assessment in the water supply sector. International Group on Reliability (I.G.O.R.), Reliability: Theory & Applications 1, 2012, pp. 142–153.

[15] Rak J.: Dopuszczane ryzyko zdrowotne związane z konsumpcją wody wodociągowej. Sigma-NOT, GWiTS, 3, 2009, pp. 12–15.

[16] Hipel K.W., Kilgour D.M., Zhao N.Z.: Risk analysis of the Walkerton drinking water crisis. Canadian Water Resources Journal, 3, 2003, pp. 395–397.

[17] Rak J., Tchórzewska-Cieślak B.: Review of Matrix Methods For Risk Assessment In Water Supply System. Journal of Konbin t. 1, z. 1. Wydawnictwo Instytutu Technicznego Wojsk Lotniczych. Warszawa 2006, pp. 67–76.

[18] Rak J.: Methods of reliability index determination concerning municipal water quality. Journal of Konbin nr 2. Wydawnictwo Instytutu Technicznego Wojsk Lotniczych. Warszawa 2008, pp. 157–174.

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