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Analysis and assessment methods of water network failure in terms of belonging to critical infrastructure

Keywords

water supply system, failure indicators, critical infrastructure

Abstract

In paper issues connected with safety and operation of the water supply system were presented. The study paid special attention to the safety aspect of water consumers in terms of belonging to critical infrastructure. In the paper the consumer risk of the first type associated with the lack or interruptions in water supply was defined, as well as the consumer risk of the second type associated with the consumption of water with incompatible quality with the regulation. The subject of risk assessment refers to the current trends in the world, which are intended to ensure the safety and comfort use of public water supplies.

1. Introduction

Collective water supply systems (CWSS) belong to critical infrastructure and their reliable and safe operation determines the development of cities and villages [1], [9], [21], [25].

Reliability and safety of CWSS have their own international legal regulations, the source of which are primarily the guidelines of the World Health Organization – WHO.

With regard to drinking water consumers safety is defined as the likelihood of avoiding the threat arising from consuming water with the quality incompatible with the existing regulation (the Regulation of the Minister of Health of 13 November 2015 on the quality of water intended for human consumption) or the lack of water. In accordance with the above mentioned Regulation water is safe for human health when it is free from pathogenic microorganisms and parasites in number constituting a potential threat to human health, also chemicals in quantities endangering the health and has no aggressive corrosive properties [33].

In practice, ensuring an adequate level of safety is possible only when all devices belonging to CWSS interact with each other in a certain way. Also it should be noted that continuous operation of the system has crucial meaning [7], [18], [23]-[24], [27].

Causes of failure in CWSS have an internal nature (resulting directly from the processes of design, construction and operation) or an external nature (resulting from natural causes in the environment or human activity). The human factor plays a very important role in the analysis of the causes of failure. It may involve errors of subsystem operators, as well as intentional or unintentional actions of third parties (vandalism or even a terrorist or cyber terrorist attack) [11], [20], [22], [32].

Some guidelines describing the fundamentals of crisis management are included in the European standard EN 15975-1:2009 Security of drinking water supply. Guidelines for risk and crisis management. Part 1. Crisis management. This document, (prEN 15975-1:2009), prepared by the Technical Committee CEN/TC 164 is gradually introduced by each EU Member State. The guidelines define recommendations for drinking water suppliers and management organisations.

The primary and basic subject to which the concept of water safety concerns is the consumer. The secondary subject is the supplier - water producer. In this regard, the risk can be considered as the consumer's risk and the manufacturer's risk. Important elements in this respect are also the environmental aspect and the principle of sustainable development in the widely understood water management. The water supply network is one of the basic elements of CWSS and its task is to distribute water in the supply area [3], [31].

2. Water network failure in terms of perspective preparing for renewal

Failures of water supply network can be affected by threats that might occur at various stages of the water supply network operation [2], [9]-[10], [13], [15], [17]-[18], [29], [30]:

- design of the water supply network:
    - errors in the location of the sections of the water supply network,
    - badly recognized ground conditions,
    - faulty choice of the water supply system route,
    - not taking into account the economic activity of the third parties,
    - incorrect standard of design solutions,
    - inaccurate valve selection, control, corrosion protection,
    - errors in the hydraulic system,
    - project made by the designer without necessary licence,
    - lack of documentation,
    - incomplete post-completion documentation,
- construction of the water supply network:
    - departure from the design in terms of pipe laying technology,
    - method of connection of individual pipe sections,
    - construction of casing pipes to go under partitions or through partitions, e.g. road,
    - corrosion protection, passive and active,
    - conducted pressure tests and other acceptance procedures,
- operation of water supply network,
    - lack of monitoring of the water supply network,
    - lack of response to small water leaks,
    - lack of emergency scenarios for water supply,
    - untrained operator personnel,
    - inconsistent protective and warning systems for water quality,
    - lack of communication with the recipients,
    - lack of telephone numbers active for 24 hrs used in case of emergency situation in water supply.

Listed threats may cause [3], [9], [18], [32]:

- cracks due to overloading,
- transverse or longitudinal cracks,
- errors in connections,
- internal or external corrosion,
- breakage.

Renewal of water supply system should be performed when we deal with the following situations in the water supply network [21], [24]-[25], [32]:

- poor technical condition due to the use of low quality materials and not careful execution,
- leaks in connections and water losses connected with them,
- deterioration of quality of water due to its secondary pollution,
- unfavourable changes in static and strength parameters affecting the safety of pipelines structural foundation.

The unequivocal assessment of the causes and sources of failures is quite difficult, it often consists of a variety of factors, design errors, mechanical or material defects, external impact or other random incidents, the movements of land or other natural disasters, operational errors, human errors, other or unknown causes [12], [17], [26].

3. Measures of water supply network failure rate

Some fundamental indicators used to perform water supply network failure analysis are [10], [21], [32]:

- the failure rate $\lambda(t)$ [number of failures·year (day)$^{-1}$] or [number of failures$\cdot$km^{-1}a^{-1}]. It is calculated as the total number of failures in the time interval by the number of analysed elements or for linear elements their length L [km] and time of observation,
- Mean Time Between Failures *MTBF* [d], which is the expected value defining operating time, ability of the system (or its components) between two consecutive failures,
- Mean Time To Repair *MTTR* [h] describes the value of time from the moment of failure until re-enable water flow on the damaged section of the water supply network,
- the repair rate $\mu(t)$ [number of repairs$\cdot$a(h)$^{-1}$] determines the number of failures repaired per time unit, it can be determined as the reverse of the mean repair time,
- Short Average Interruption Frequency Index, indicator of the average number of short interruptions in water supply per recipient (or connection point) covers interruptions in water supply less than 2 hours, the so-called: short breaks,
- Long Average Interruption Frequency Index, indicator of the average number of interruptions in water supply per recipient (or connection point), does not include interruptions in water supply less than 2 hours,
- indicator of interruptions in water supply, the number of interruptions per year per customer.

This indicator is calculated by dividing the number of excluded recipients during the year by the number of all the recipients,

- Customer Hours Lost, indicator of the total duration of interruptions in the supply of water per recipient, it is the quotient of the annual duration of interruptions in water supply (in hours) to the number of recipients,
- Average Not Supplied Water Volume, the average annual amount of water not delivered to one recipient,
- Customer Average Interruption Duration Index, the average duration of interruptions in water supply, it is the quotient of the total number of interruptions in the supply of water per year to the number of excluded recipients,

From the point of view of water consumers and producers the consequences of failure in water pipe network are dependent on the size and frequency of failures and their duration. From the producers point of view very important are water losses. The volume of water that enters the canals or ground due to the leakage from network greatly depends on the size and kind of failure, duration of outflow and pressure in the region of failure [6], [12]-[13]. Additional losses associated with the occurrence of failure of water supply network are connected with the necessity of washing pipes after repair.

4. Methods of analysis and assessment of the risk of failure in the water supply system

Risk management can be defined as the socio-economic decision-making process [4]-[5], [28]. It is impossible to eliminate risk, only various actions can be taken as to minimize it to an acceptable level from the point of view of safety and necessary costs, which is said in the rule called ALARP - *As Low As Reasonably Practicable*.

Risk assessment is a comparison of the determined values with the criteria values of acceptability of risk, which is a base for safety analysis. At this stage it is very important to define the criteria of acceptability of risk, so that they can be used in decision-making process regarding the system operation (e.g. renovations or modernization). Such criteria should take into account the requirements related to the reliability of subsystem functioning (in terms of both quantity and quality, in accordance with applicable legal norms and with social and economic conditioning).

Generally, risk analysis methods are divided into [17], [32]:

- quantitative methods for risk analysis - QRA - these are the methods that process the quantitative (measurable) data and determine the specific value of risk. These methods include methods based on mathematical statistics and the probability calculus,
- qualitative methods of risk analysis - QLRA – as opposed to the quantitative methods these methods do not include the numerical determination of risk using probabilistic methods (e.g. density distributions),
- quantitative-qualitative methods for risk analysis, which include, among others, matrix methods, Fault Tree Analysis (FTA) and Event Tree Analysis (ETA), Bayesian networks, fuzzy logic and neural networks,

simulation methods using computer models of hydraulic and control systems, processing and recording data (SCADA), computerized databases, e.g. GIS (Geographic Information System), as well as Monte Carlo simulation method. They are a tool to support the process of risk analysis.

If there are many undesirable events that can cause losses the risk is summed as follows [20]:

$$R = \sum_{i=1}^{n} P_i \cdot C_i \qquad (1)$$

where P_i is the probability that *i*-th undesirable event occurs in time unit ($i = 1, 2, ..., n$), C_i is the consequences of the *i*-th undesirable event in time unit an *n* is number of undesirable events.

S. Kaplan and B.J. Garrick [8] interpret risk as a set of products of probabilities and consequences. By grouping it ascending in terms of probability, a vector of risk can be determined in the form of the equation, that illustrates the so-called risk curve (*Figure 1*):

$$R_x = \{P_1 \cdot C_1, P_2 \cdot C_2, \ldots, P_n \cdot C_n\} \qquad (2)$$

where $r_1 = P_1 \cdot C_1$ and $x = A, B, \ldots, n$

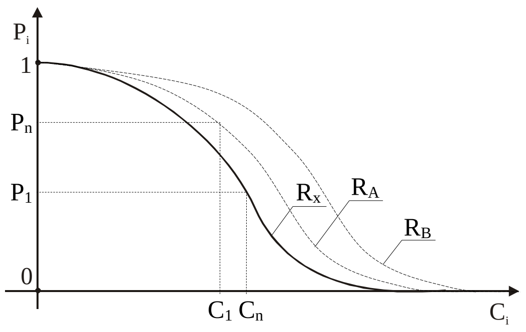

Figure 1. Risk curve, own study based on the work [8]

5. Risk of water producer and water consumer

The risk of water producer r_p is defined as follows [32]:

$$r_p = E(C)/E(Z) \tag{3}$$

where $E(C)$ is an expected value of losses incurred as a result of undesirable events occurrence (losses associated with the lack of water sales, the need to repair and flushing water pipe network, possible compensation for water consumers) and $E(Z)$ is an expected value of water company financial profit resulting directly from the water sale.

Consumer's risk (individual) r is the sum of the first kind risk r_{KI}, associated with the possibility of interruptions in water supply, and the second kind risk r_{KII}, associated with the consumption of poor quality water [32].

Consumer's risk is a function of the following parameters:

- a measure of probability (P) of undesirable events occurrence in water distribution system (WDS), which are directly felt by water consumers,
- losses (C) connected with undesirable events occurrence, e.g. the purchase of bottled water, medical expenses after consuming bad quality water or immeasurable loss, such as existentially-economic difficulties or life or health loss,
- the resistance degree (Res) to undesirable events or the degree of protection against undesirable event (O).

The risk of consumer r is described by the formula [32]:

$$r = r_{KI} + r_{KII} \tag{3}$$

where r_{KI} is the risk of a first type and r_{KII} is the risk of the second type.

For the risk of the first type the three-parametric definition is assumed:

$$r_{KI} = (P_{iI} \cdot C_{jI} \cdot Res_{kI}) \tag{4}$$

where i is the proposed scale for the probability parameter, j is the proposed scale for the consequences parameter, k is the proposed scale for the resistance parameter, P_{iI} is the probability of the undesirable event occurrence that may be the cause of the first type risk, C_{jI} is the value of losses caused by the undesirable event, which may cause risk of the first type, Res_{kI} is the resistance associated with the occurrence of the undesirable event, which can be the cause of the first type risk and N_I is the number of undesirable events.

Risk criteria were developed on the basis of own research and the literature study [4], [7], [9]-[10], [18]-[21], [30], [32].

The following descriptive-point scale and weights of the individual parameters are proposed:

- category of probability – P range of the undesirable events:
  - low probability, once in five years, ≤ 0,2 failure/a, point weight = 1,
  - medium probability, once in 2 years, from 0,2 to 0,5 failure/a, point weight = 2,
  - moderate probability, once in 0,5 year, from 0,5 to 2,0 failure /a, point weight = 3,
  - high probability, once a month and more often, ≥ 12 failure/a, point weight = 4,
- category of losses - C:
  - small losses, local decrease in water pressure in the water mains, individual consumer complaints, perceptible interruptions in the water supply to consumers living on the upper floors of buildings, point weight = 1,
  - average losses, decrease of the daily water production Q_{dmax} to 70% of the nominal value Q_n or interruptions in the supply of water lasting up to 8 h, point weight = 2,
  - big losses, decrease in daily water production Q_{dmax} from 30 to 70% of the nominal value Q_n or interruptions in water supply from 8 to 24 h for consumers in individual housing estates, point weight = 3,
  - very big losses, decrease in daily water production Q_{dmax} to less than 30% of the nominal value Q_n, failure of the main water pipe line, lack of water lasting more than 24 hours for individual housing estates, districts or the whole city, significant losses both financial and social, point weight = 4.
- category of resistance - Res:
  - very high resistance, standard monitoring of the water supply network with measurements of pressure and flow rate, the ability to cut off the damaged section of the network by means of gates, the network in the open and mixed system, emergency early warning and response system, the availability of alternative sources of water, point weight = 1,
  - 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 mains standard monitoring, measurements of pressure and flow rate, system of delayed warning, alternative water sources do not cover the

needs completely, point weight = 2,
- low resistance, the inability to cut off the damaged section of the network by means of gates without interrupting water supply to customers, the network in the open system, limited water mains monitoring, system of delayed warning in crisis situations, limited access to alternative water sources, point weight = 3,
- very low resistance, lack of emergency warning and response system, 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, lack of water mains monitoring, very limited access to alternative water sources, point weight = 4.

For the second type of consumer risk the following definition was assumed:

$$r_{KII} = (P_{iII} \cdot C_{jII} \cdot Res_{kII}) \qquad (5)$$

where P_{iII} is the probability of the undesirable event occurrence that may be the cause of the second type risk, C_{jII} is the value of losses caused by the undesirable event which may cause risk of the second type, Res_{kII} is the resistance associated with the occurrence of the undesirable event which can be the cause the second type risk and N_I is the number of undesirable events.

The criteria for the probability and resistance parameters were adopted analogously as for the risk of the first type. The descriptive-point scale for the parameter C is as follows:
- small threat, perceptible organoleptic changes of water (odour, colour change and turbidity, with the existing minimum risk of further water quality deterioration), local deterioration of water quality parameters, water consumers complaints, no health threat for consumers, point weight = 1,
- average threat, a significant organoleptic nuisance, as odour, colour change and turbidity, numerous complaints, information in local public media, danger to the consumers health, the physico-chemical indicators exceeded, lack of pathogenic microorganisms, point weight = 2,
- big threat, information in local public media, problems with consumers health, the possibility of the escalation of events, the so called domino effect can occur, exceeding of the physical and chemical indicators, secondary water pollution in different parts of the water supply system, a large group of consumers can be exposed to the consumption of deteriorated water, the possibility of pathogenic microorganisms occurrence, point weight = 3,
- very big threat, indicator organisms reveal high levels of toxic substances, the possibility that a large group of consumers can be exposed to the consumption of deteriorated water, the involvement of professional emergency services, the information in the national media, the physical and chemical indicators exceeded and/or the pathogenic microorganisms occur, the secondary water pollution in the water supply system, affected people must be hospitalised, point weight = 4.

In this way, the point scale of risk measures from 1 to 64 was obtained. In the *Table 1* a three-parameter risk matrix was presented.

The presented point weight scales are the suggestion for the initial risk assessment and can be modified for the given CWSS. The advantage of the presented method and procedure is the ability to compare risk in different CWSS. The parameters scales describing risk at different levels of its occurrence should be as simple as possible, which will allow the assessment and classification for each considered scenario of undesirable event occurrence.

The following risk categories and corresponding point scales were assumed, according to risk matrix (*Table 1*):
- tolerable risk category, r_t from 1 to 8,
- controlled risk category, r_c from 9 to 24,
- unacceptable risk category, r_{un} from 32 to 64.

In case of a tolerable risk it is required to perform threat monitoring in order to keep it in this category. In case of a controlled risk it should be reduced to tolerable values. In case of an unacceptable risk it is necessary to take measures to reduce it. When an unacceptable risk occurs the CWSS should be excluded from exploitation.

Exemplary application of the proposed method

The population of the city is supplied with drinking water from a central water system. Water supply system functioning is based on the limited monitoring and limited access to alternative sources of drinking water (low resistance, point weight = 3). Exposure to threat is moderately likely, once in 0,5 year, point weight = 3.

Threat to the consumer health occurs in the form of exceeding physico-chemical indicators, lack of pathogenic microorganisms, but a significant organoleptic water nuisance (average threat, point weight = 2).

Based on the analysis the controlled risk was obtained. Remedial measures, such as increasing the monitoring frequency of water supply network, considering the possibility of introducing alternative water sources, should be taken.

Table 1. Three-parameter matrix for estimating the consumer risk when an undesirable event occurs

P	C	Res			
		1 - very high resistance	2 - medium resistance	3 - low resistance	4 - very low resistance
1 - low probability	1 - small threat	1	2	3	4
		r_t	r_t	r_t	r_t
	2 - average threat	2	4	6	8
		r_t	r_t	r_t	r_t
	3 - big threat	3	6	9	12
		r_t	r_t	r_c	r_c
	4 - very big threat	4	8	12	16
		r_t	r_t	r_c	r_c
2 - medium probability	1 - small threat	2	4	6	8
		r_t	r_t	r_t	r_t
	2 - average threat	4	8	12	16
		r_t	r_t	r_c	r_c
	3 - big threat	6	12	18	24
		r_t	r_c	r_c	r_c
	4 - very big threat	8	16	24	32
		r_t	r_c	r_c	r_c
3 - moderate probability	1 - small threat	3	6	9	12
		r_t	r_t	r_c	r_c
	2 - average threat	6	12	18	24
		r_t	r_c	r_c	r_c
	3 - big threat	9	18	27	36
		r_c	r_c	r_{un}	r_{un}
	4 - very big threat	12	24	36	48
		r_c	r_c	r_{un}	r_{un}
4 - high probability	1 - small threat	4	8	12	16
		r_t	r_t	r_c	r_c
	2 - average threat	8	16	24	32
		r_t	r_c	r_c	r_{un}
	3 - big threat	12	24	36	48
		r_c	r_c	r_{un}	r_{un}
	4 - very big threat	16	32	48	64
		r_c	r_{un}	r_{un}	r_{un}

6. Conslusions

The risk matrices can be applied for different CWSS and their subsystems. For safety and stable functioning of CWSS very important is the categorization of risk levels: tolerated, controlled and unacceptable.

From the operator point of view, very important is the ability to analyse protection in order to minimize the risk associated with the CWSS operation. In the risk failure analysis historical knowledge of the system operation should be used, as well as the analytical methods and experience.

The presented method has an expert character and requires the cooperation of designers, contractors and exploiters of water supply system, which gives the opportunity to connect experts knowledge in a given field and allows taking into account all important factors affecting the risk associated with the undesirable event occurrence in the CWSS.

Of course, it is impossible to eliminate risk, only various measures aimed at its reduction to an acceptable level from the point of view of water consumers safety and the costs incurred by the water companies, can be taken.

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