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Risk analysis of water supply interruptions in collective water supply systems

Keywords

water supply, availability, risk management, value of water scarcity, water production subsystem

Abstract

The subject and main purpose of this study is to present the method of risk analysis and assessment of the lack of water supply to the collective water supply system (CWSS). Presented method using the expected value of water scarcity. The analysis was based on all possible states of the operation of water production subsystem. The article contains calculation example of analysis for the exemplary CWSS with regard to absolute risk, equal to the expected value of water scarcity and the relative risk referred to the nominal value of the water demand. In the example attached special importance to the criteria levels of the relative risk of lack of water supply. Presented method is a new concept which allows to make comprehensive analysis of reliability, safety and operation of the collective water supply system.

1. Introduction

Safety of collective water supply system (CWSS) has its own international legal regulations whose primarily source are the guidelines of the World Health Organization - WHO. With regard to drinking water consumers, safety is understood as the probability to avoid threat arising from the consumption of water inconsistent with quality standards or the lack of water. Water is safe for human health if it is free from pathogenic microorganisms and parasites in the amount constituting a potential threat to human health, any substances in quantities hazardous to health and has no aggressive corrosive properties. The collective water supply system is created by the systems forming an integral whole and having different functions. Most real technical systems are very complex and it is difficult to analyze their safety [9]. The collective water supply system can be divided according to the diagram:

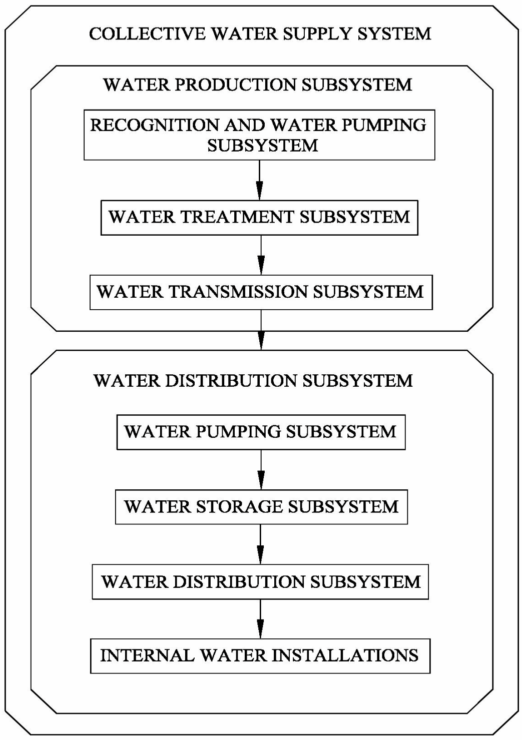

Figure.1. Blok diagram of the collective water supply system

Water supply reliability means providing stable conditions allowing to meet current and future demand for water in sufficient quantity and with required quality, in convenient time for water consumers and also at a price acceptable by them. Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption and the Frame Water Directive has committed the EU member states to monitoring the quality of water intended for human consumption. The member states should take all necessary measures to ensure regular monitoring of water quality. The aim of monitoring is to check if water is available to consumers meets the requirements of current international legal regulations. In 2004, in the third edition of Guidelines for Drinking-Water Quality, the WHO presented the guidelines for the development of the so-called Water Safety Plans (WSP), which are intended for collective water supply systems and are based on a comprehensive risk analysis in the CWSS subsystems to ensure water consumers safety.

Critical infrastructure (which includes the CWSS) means the systems critical to national security and the citizens. In 2009, the project of European standard pr EN 15975-1:2009: Security of drinking water supply. Guidelines for risk and crisis management. Part1. Crisis management, which will be gradually introduced in the particular member states, was developed.

In the security issues of the CWSS we distinguish the following terms:

- Safety Related System - SRS, based on Independent Safety Layer - ISL. The ISL includes Independent Protection Layer and Independent Mittigation Layer. The multi-layer security system has a serial structure and if the lower layer executed its task successfully, the higher-level layer does not need to be started,
- Safety Integrity – SI,
- Safety Integrity Level - SIL,
- Safety Interlock System – SIS.

The primary and basic subject to which the notion of water safety is concerned is a consumer. The secondary subject is a supplier – a manufacturer of water. In this respect, one can consider the risk of the consumer and the producer. The important elements in this regard are also the environmental aspects and the principles of sustainable development in water management. Reliability and safety of the CWSS operation are achieved through risk management at every stage of the " system life" - at the design stage, during construction and operation [11], [14], [17].

The definition of the CWSS safety, including technical, economic and environmental aspects, is the following:" safe CWSS operation means ensuring continuity of water supply to the consumer while the following criteria are met [10]-[11]:

- system reliability (in terms of quantity, quality and quantity - quality),
- socially acceptable level of prices per m^3 of delivered water, taking into account aspects arising from the requirements for public safety, natural aquatic environment protection and standard of life quality.

The main objective of this paper is to present the method of risk analysis and assessment of the lack of water supply to the CWSS, using the so-called expected value of water scarcity. The proposed method is based on the analysis of all possible states of the operation of water production subsystem. The method distinguishes the absolute risk, equal to the expected value of water scarcity and the relative risk, expressed as a percentage and referred to the nominal value of the water demand. For the relative risk the criterial values of risk assessment were proposed, based on operational experience. Using the method of water scarcity in the CWSS risk analysis is a new concept which allows to make comprehensive analysis of reliability, safety and operation of Water Production Subsystem (WPS), (according to Figure 1), for the risk of lack of water supply to the CWSS.

The presented method can be used in operation of the CWSS, as well as in water supply safety management in the crisis situations. The method assumes the possibility of the WPS unreliability as a result of:

- failure of the particular components of the subsystem,
- contamination of drinking water by harmful or dangerous substances, understood as an incidental undesirable event.

Poor quality drinking water supplied to the CWSS can lead to the loss of water consumers safety [12], [15]-[16]. The presented method can be classified as the quantitative and qualitative method. The paper presents a calculation example, paying particular attention to the criterial levels of the relative risk of lack of water supply.

2. Risk analysis of lack of water supply using the expected value

Risk is a measure which defines the safety level of water supply systems [5], [8].

They introduced the following mathematical: definition of risk r [1], [6], [18]:

$$r=\{S_i,P_i,C_i\},$$

where:

- S_i denotes the - the risk scenario,
- P_i denotes the likelihood of that scenario,

- *C* denotes resulting consequences.

Hastak and Baim [7] define the infrastructure risk as the product of the probability (likelihood) of system failure and associated costs of returning the system to service. To perform effective risk assessment and management, the analyst must understand the system and its interactions with its environment, and this understanding is requisite to modeling the behavior of the state of the system under varied probabilistic conditions. 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 operation is carried out [4], [13]. 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]-[3], [16]:

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

A factor determining the risk of lack of water supply to the CWSS can be a scarcity of water production during the failure of the particular subsystems of water production. Water scarcity can be caused by the unreliability of the production subsystem, for this reason the assessment of the reliability of water supply to customers is especially important [13], [15].
It is assumed that the absolute risk of lack of water supply is a product of the probability of water scarcity and the losses associated with it. This relation can be determined using the so-called expected value of water scarcity E(ΔQ):

$$r_{bN} = E(\Delta Q) = \sum_{i=0}^{i=n} \Delta Q_i \cdot P_i \qquad (1)$$

where:

- r_{bN} – the absolute risk of water scarcity,
- E(ΔQ) – the expected value of the deficiency of water sources,
- i – a number of the WPS operating state,
- n – a maximum number of the possible states of reliability; n = 2m (m – a number of all water sources of the CWSS),
- ΔQ_i – deficiency of water sources in the given state of unreliability,
- Pi – probability of the i-th state of operation of the water production subsystem (WPS).

The value of the deficiency of water sources ΔQ is calculated as the difference between the required capacity of water sources and the capacity of sources in the i-th state, according to the formula:

$$\Delta Q = Q_n - \sum_{k_i}^{k_i} Q_{ik} \qquad (2)$$

where:

- Q_n – the required water demand, the required system capacity during the normal operation (usually the value of Qnis assumed to be the maximum daily demand for water Qmaxd or the design value of water production),
- k_i – a number of faulty water sources in the i-th state,
- Q_{ik} – production of the particular water sources in the i-th state with ki failures.

The value of the probability P_i is determined by the formula:

$$P_i = \prod_{j \in S} K_j \cdot \prod_{j \in N} (1 - K_j) \qquad (3)$$

where:

- K_j – the availability index of the j-th water supply subsystem,
- $j \in S$ – the set of those subsystems of delivery (or their components) that are efficient in the i-th state, marked with the symbol (+),
- $j \in N$ – the set of those subsystems of delivery (or their components) that are inefficient in the i-th state, marked (–).

In order to assess the risk of lack of water supply, the relative risk of lack of water supply to the CWSS is defined, addressing the expected value of water scarcity (the absolute risk) to the nominal value of water supply, which also allows to determine the criteria values. In order to better illustrate the relative risk its value can be expressed as a percentage, according to the formula:

$$r_{wN} = \frac{r_{bN}}{Q_n} \cdot 100\% \qquad (4)$$

where:

- r_{wN} – the relative risk of lack of water supply [%],
- Q_n – the nominal value of the water demand [m^3/d].

If the sum of the capacity of all sources is greater than the required capacity, then the so called water reserve occurs. (scarcity is equal to zero).
The proposals for criteria for the assessment of the absolute risk are presented in *Table 1*. These criteria were developed based on literature studies and according to the CWSS reliability category given in the studies.

Table 1. The criterial values for the levels of the relative risk of lack of water supply

Water pipe category	r_{wN} [%]	Risk level
I – large water pipes, number of inhabitants > 500 000	≤2	tolerable
	(2÷5)	controlled
	≥ 5	unacceptable
II – medium water pipes, number of inhabitants 50 000÷500 000	≤3	tolerable
	(3÷8)	controlled
	≥8	unacceptable
III – small water pipes, number of inhabitants ≤ 50 000	≤5	tolerable
	(5÷8)	controlled
	≥ 8	unacceptable

3. Calculation example

The analysis of the exemplary CWSS for the city of X, with a total population of 100 000, was made. Water pipes were classified as the category II, according to *Table 1*. The city is supplied by two independent WPS, which include: water intakes, treatment plants and treated water pumping stations. The nominal value of the water demand equal to the maximum daily water demand: $Q_n = Q_{max} = 55\,500$ m3/d was assumed.
The capacity of the particular systems of the WPS and the corresponding availability indexes K [14] are presented in *Table 2*. On the basis of the adopted data and the determined expected value of water scarcity (formula (1)) the relative risk and the absolute risk of lack of water supply to the CWSS were calculated.

Table 2. The values of water production and availability indexes K for WPS I and WPS II

WPS	Q [m^3/d]	K
WP1	37 000	0,9659
WP2	47 000	0,9870

∑Q = 84 000

The calculations were carried out in two variants:
Variant I. The system operates with excess, the nominal value of the water demand is lower than the sum of the capacity of both subsystems the WP1 and WP2 : Q_n,< ∑Q.
Variant II. Two cases of system operating with deficiency were considered:

- The WPS WP1 is working, the nominal value of the water demand is greater than the water source WP1 capacity : Q_n,> QWP1
- The WPS WP2 is working, the nominal value of the water demand is greater than the capacity of the water source WP2: Q_n,> QWP2.

3.1 The calculations for Variant I

Table 3 presents the results of calculations of the absolute risk, according to the formulas: (1) ÷ (3) for the nominal value of the water demand: Q_n = 55 500 m3/d. For the two water sources the number of the possible states of reliability is: n = 2m → 4 = 22, where "m" represents the number of all the CWSS water sources. The state of reliability is marked with '+', the state of unreliability with "- ".

Table 3. The results of the analysis of the absolute risk of lack of water supply for the city of X

i	Characteristics of operating states		Capacity [m^3/d]		Total [m^3/d]	Deficiency [m^3/d]	Indexes K		Probability of i state	$P_i \cdot \Delta Q$
	WP1	WP2	Q_{ZI}	Q_{ZII}	Q	ΔQ	K_{ZI} lub $(1-K_{ZI})$	K_{ZII} lub $(1-K_{ZII})$	P_i	
1	+	+	37000	47000	84000	0	0,9659	0,987	0,953343	0
2	+	–	37000	0	37000	18500	0,9659	0,013	0,012557	232,30
3	–	+	0	47000	47000	8500	0,0341	0,987	0,033657	286,08
4	–	–	0	0	0	55500	0,0341	0,013	0,000443	24,59
∑									1	542,97

The absolute risks of lack of water supply to the CWSS is:

r_{bN} = 542,97 m^3/d.

The relative risk was calculated using the formula (4) for the water demand: Q_{maxd} = 55 500 m^3/d.

The relative risk of lack of water supply:

r_{wN} = 0,98 %.

According to the data contained in Table 1, the relative risk of lack of water supply to the CWSS for the city of X, for a variant of WPS working with an excess, is on a tolerable level.

3.2 The calculations for Variant II

In *Tables 4* and *5* the results of the calculation of the absolute risk for the subsystem operating with a deficiency are shown. One of the two WPS: WP1 or WP2 is working.

The analysis of the particular subsystems operating allows to perform the analysis for the possible exclusion from the operation of one of them for economic reasons.
The nominal value of the water demand is:
$Q_n = Q_{maxd}$ = 55 500 m^3/d, one of the two WPS is working: WP1 or WP2.

- WP1 is working: Q = 37 000 m^3/d (the system with deficiency).

Table 4 presents the results of the calculations for a hypothetical state: only WP1 is working.

Table 4. The results of the absolute risk analysis of lack of water supply

Characteristics of operating states		Capacity [m^3/d]	Deficiency [m^3/d]	K or 1 – K	Probability of i state	$P_i \cdot \Delta Q$
i	WP1				P_i	
1	+	37 000	18 500	0,9659	0,9659	17869,15
2	–	0	55 500	0,0341	0,0341	1892,55
∑					1	19761,70

The absolute risks of lack of water supply to the CWSS is:

r_{bN} = 19761,70 m^3/d.

The relative risk calculated from the formula (4) for the maximum water demand Q_{maxd} = 55 500 m^3/d.

The relative risk of lack of water supply:

r_{wN} = 35,61 %.

Comparing the obtained results with the data in *Table 1* for water pipe category II (population = 100 000), the relative risk of lack of water supply to the CWSS for the state in which only WPS WP1 is working, is on the unacceptable level.

- WP2 is working: Q = 47 000 m^3/d (the system with deficiency).

Table 5 presents the results of the calculations for a hypothetical state: only WP2 is working.

Table 5. The results of the absolute risk analysis of lack of water supply

Characteristics of operating states		Capacity [m^3/d]	Deficiency [m^3/d]	K or 1 – K	Probability of i state	$P_i \cdot \Delta Q$
i	WP2				P_i	
1	+	47 000	8500	0,987	0,987	8389,50
2	–	0	55 500	0,013	0,013	721,50
∑					1	9111,00

The absolute risks of lack of water supply to the CWSS is:

r_{bN} = 9111,00 m^3/d.

The relative risk calculated from the formula (4) for the maximum water demand Q_{maxd} = 55 500 m^3/d.
The relative risk of lack of water supply to the CWSS:
r_{wN} = 16,42 %.

Comparing the results with the data in *Table 1* for water pipe category II (population = 100 000), the relative risk of lack of water to the CWSS for the state in which only WPS WP2 is working, is on an unacceptable level.
After the calculations it can be seen that the CWSS for variant I (the system operates with excess) meets the criteria for the risk of lack of water supply to the distribution subsystem. In the case of variant II (the system with deficiency), WP1or WP2 excluded from the operation, the criteria given in Table 1 are not met because the risk of lack of water supply is on the unacceptable level. The analysis showed that the best solution is to use both subsystems.

4. Conclusions

- Constantly occurring threats, such as floods, droughts, electrical power failures, accidental contamination of water sources, and even terrorist attacks and cyber terrorist attacks, can often lead to serious disruptions of the CWSS subsystems operating.
- The identification of risk in the CWSS and ensuring safety means primarily to recognize the threats, to develop scenarios of the undesirable events and to estimate threat to lives or health of water consumers.

- The management of risk connected with the CWSS can be defined as a process of coordination of the operation of the CWSS elements and its operators, using available means, in order to obtain the tolerable risk level in the most efficient way, as far as technology, economic and reliability are concerned. The exploitation of urban CWSS should take into account the minimization of water losses, operational and safety reliability. The main purpose of the decident is to make the right choice that means to choose the best alternative which will assure them the best results in their economical activity.

- Also the CWSS itself can cause a crisis situation when various scenarios of undesirable events, which can cause system operating unreliability, and in consequence, the loss of water consumers safety, occur. Therefore, the development of plans for drinking water supply in emergency, for various critical situations, as well as the detailed analysis of risk of the possibility that undesirable events in the CWSS will occur, in order to develop a complex program of the system safety management, is so important. The goal of the paper is to demonstrate the value of an objective risk assessment tool for estimating the CWSS decision-maker's sensitivity to failure risk. The usefulness of the objective risk assessment tool was demonstrated by defining three risk-sensitive (tolerable, controlled and unacceptable) decision response alternatives that are encountered by the typical CWSS decision-maker.
- Risk analysis and assessment of lack of water supply to the CWSS should refer to any possible undesirable events, as well as to the least likely events.

- Proper assessment of the reliability and safety of the CWSS should be the guarantor of making the right decisions in choosing the best solutions in technical, economical and operational terms. The methods for the analysis of the reliability and safety of the collective water supply systems, developed for many years, contributed significantly to improving the system operation, thereby improving the usability of municipal water pipeline.

- The method of risk analysis, using the concept of the expected value of water scarcity, allows the analysis and assessment of the risk of lack of water supply, including different combinations of the reliability states of the water production subsystem (water sources, treatment plant and pumping station).

- Risk assessment at the design, construction and operation stage helps to reduce the risk of the CWSS operating and to ensure safety of water supply to customers.

- The presented method will help to improve the reliability of the CWSS, taking into account the quantitative and qualitative aspects.

- The ability of risk assessment allows to develop the methodology of risk management based on the concept of cause and effect, and also to set the hypothesis that the case is only a measure of our lack of knowledge.

- The analysis demonstrated that for the correct operation of the entire CWSS is required work of both water intakes (WP1 and WP2).

- In case of failure of both subsystems, analyzed system has a water storage tanks, which provide an emergency demand for water for one day. If the failure of subsystems will be longer than one day, it is required to provide drinking water in bottles or by water-cart.

- The concept of expected value of water scarcity is widely used in reliability analysis of CWSS.

- The proposed method is a proposal to use existing researches of reliability water supply system in risk analysis of lack of water supply to the water distribution subsystem (WDS) as a result of failure of water sources.

- The limitation of using this method is necessity to have a reliability index K for subsystem, which is not always available.
- The method can be used in making decision such as extension or modernization of existing water sources.

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