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Crisis situation management issues in urban areas water supply

Keywords

water supply system, crisis situation, critical infrastructure

Abstract

In paper the methods of comprehensive analysis of reliability, safety and operation of the water supply system were presented. The main goal of this work is to present the problems associated with the WSS functioning in terms of belonging to critical infrastructure. The analysis of the WSS functioning in face of emergency events occurrence should be one of the priority actions taken by the water companies. The paper presents an application of reliability and safety analysis of water supply in emergency situations.

1. Introduction

Civilization conditions cause increased interest in problems connected with municipal systems safety management, especially when a critical situation occurs. The European Union Directive 98/83/EC and the World Health Organisation (WHO) guidelines committed European Union Member States to monitor the quality of water intended for human consumption. In 2004 the WHO provided guidelines [37] for the development of the so-called Water Safety Plans, which are designed for Water Supply Systems (WSS). The Water Safety Plan (WSP) is a key element of the strategy for preventing undesirable events in all CWSS subsystems [36], [38]. The WSP includes: the basic characteristics of the aim of WSP, which is to ensure water consumers safety, an overall assessment of CWSS - including the answer to the question whether the water supply system - from the water intake through water treatment, up-to-consumption - is able to provide water that meets health standards in accordance with the applicable regulations, management plans, validating monitoring for each WSS subsystem conducted in order to confirm that the implemented WSP procedures allow to achieve the planned objectives [41]. Emergency type events in Water Distribution Subsystem (WDS) are divided primarily on [19], [31], [33]:

- failures of water pipes and fittings,
- secondary water contamination in water supply network,
- incidental events causing a lack of water supply for distribution subsystem, for example, water source contamination, water treatment plant failures, water contamination in network water tanks,
- failures in water pump stations.

The consequences of the above mentioned events are [23]:

- lack or interruption in water supply to consumers,
- threat to consumers health due to the consumption of poor quality water,
- water company financial losses incurred because of the lack of water sales and the necessity to remove failure, to rinse the network, to pay compensations to water consumers,
- consumers financial losses related to, for example, the necessity to buy bottled water, to pay for treatment, to bear costs resulting from sanitary and hygiene related problems.

The most common undesirable events in WDS are failures of pipes of water supply network and its fittings. In most cases damages of fittings do not cause a direct threat to water consumers. It also applies to leaks in water pipes which do not cause the necessity to exclude the segment of network from exploitation [15].

Due to a specific character of water-pipe network operating, the system of failure repair is inseparably connected with the maintenance of network operational reliability and a priority is to provide consumers with good quality water, at the appropriate pressure, at any time [26].

Water supply system failures are a major problem in the process of system operation. Failures of this type include: the body of the pipe, connectors and compensators, fittings (gates, valves, hydrants, vents and drains, etc.). They may be caused by a single random events or human intervention or are the result of the combined action of time, excessive stress and/or local unfavourable environmental conditions [7], [27], [32].

The reasons for the failure of water supply network can also be wrongly assumed concept of the structure of the water supply network, wrongly chosen hydraulic conditions of the network (too high working pressure, lack of fittings protecting against hydraulic impacts), the corrosivity of ground, temperature changes, etc. [18], [25]. The comprehensive analysis of the water supply system failure can be found in the monograph by M. Kwietniewski, J. Rak [12], where the extensive data and the analyses of the results of the national studies made so far, were collected.

The CWSS safety management is an activity of a leading operator involving determining objectives (preventing lack of water supply or poor quality water that endangers the health of consumers using public water pipeline) and their success with the use of processes, information resources in the given operating conditions, in accordance with the applicable law and reasonably economically. A special case of WSS safety management is system management in a crisis situation [35].

The main aim of this paper is to present the problems associated with the WSS functioning in terms of belonging to critical infrastructure.

2. Legal status of WSS safety management in crisis situations

Chapter XI of the Constitution of the Republic of Poland titled “Extraordinary Measures” defines situations of particular danger, in which ordinary constitutional measures are inadequate and a state of natural disaster may be introduced. A legislator defines the notion of a state of natural disaster as a natural disaster or a technological failure whose consequences threaten health of a large number of people, a great amount of property or a significant area of the environment, and help and protection can be taken effectively only by using extraordinary measures, when different bodies and institutions, as well as special services and teams act under joint management. A state of natural disaster may be introduced to avoid the consequences of natural disasters (e.g. flood, draught, etc) or of technological accident exhibiting characteristics of a natural disaster and to remove them. In the article 3 of Act on a State of Natural Disaster the notion of natural disaster is defined as an event resulting from processes of nature. Technological accident, however, according to this act, is an abrupt and unexpected damage or destruction of a building, machine or any other technical device placing them temporarily out of order or depriving them of their main features. A disaster having enormous size is called a cataclysm, secondary effects of disasters are infectious diseases, epidemics, natural environment destruction [20]-[21]. A catastrophic event in a macro scale is defined by the World Health Organisation (WHO) as such event whose occurrence and consequences cannot be combated by an affected society itself, and the outside help is needed [41]. The notion of a serious failure and a serious industrial failure was introduced by the *Act* of *27 April 2001 Environmental Protection Law*. According to this act a serious failure means an event, especially emission, fire or explosion during an industrial process, storage or transport, in which one or more dangerous substances occur, leading to an immediate or delayed threat to people’s lives, health, environment. A serious industrial failure means a serious failure in a plant. On 26 April 2007, the Act on Crisis Management was passed (this act abolished Act on a State of Natural Disaster), which defines a procedure which should be used when there are no conditions to introduce one of the constitutional extraordinary measures (chapter XI of the Constitution). The act defines a crisis situation as a situation resulting from the threat and leading, in consequence, to break or considerable damage of social bonds, with, at the same time, significant restrictions on the operation of the competent authorities of public administration in such degree, however, that used measures necessary to ensure or restore safety do not justify the introduction of any of the extraordinary measures given in article 228 section 1 of the Constitution of the Republic of Poland. The measures necessary to ensure or restore safety are defined by the Act on Crisis Management as an activity of public administration bodies, being an element of national safety management, which aim is to prevent crisis situations, to prepare to control them using the planned actions, to response when crisis situation occurs and to reconstruct critical infrastructure.

3. Water supply in emergency situations

Technical and organizational requirements for the design and operation of CWSS are given by the currently not valid Ordinance of the Minister of Economy, Planning and Construction on the rules to ensure the operation of public water supply facilities in special conditions, which can be used by water companies to develop emergency plans for water supply. In accordance with the above guidelines in crisis situation water company should: increase the dose of disinfectant, activate alternative water treatment technologies, omitting Water Treatment Plant (e.g. water supplied by tanks and water carts). Treating water delivered from reserve intakes in the necessary amount should be ensured in technological systems adapted for the removal of water contamination in water treatment plants, transportable water treatment plants and special filters. The minimum water pressure in water network for the municipal water pipeline should be 0.1 MPa, for rural water pipeline 0.06 MPa. If the CWSS does not operate and in the areas not covered by the water supply network, water is provided from emergency wells.

One can distinguish two kinds of water requirements in crisis situation:

- the necessary water quantity (for a few weeks' time): people - 15 dm^3/person·day, public utility - 50% of their normal demand, industrial plants – quantity necessary to guarantee operation, water pipeline needs: 5-15% of daily production, fire protection - depending on needs and specific character of the area, as determined by the relevant fire brigade,
- the minimum water quantity (for a few days' time): people - 7.5 dm^3/person·d.

In a crisis situation drinking water supplied to water pipe network in the necessary quantity should be taken, if possible, from the underground water intakes, the other intakes in those conditions become the reserve intakes. Water pipeline should have the possibility to:

- cut off given water intakes with the operational possibility to use the whole system or its fragments, e.g. water pipe network, water intake, transit water pipes.
- activate alternative water treatment technology (e.g. periodical dosage of active carbon in a powdery form),
- increase the dosage of disinfecting agent,
- supply water omitting Water Treatment Plant.

If the water pipeline does not operate and in the areas not covered by water pipe network, water is supplied from emergency wells. When a number of emergency wells are too low or their layout is unfavourable one should predict water delivery by tanks or water-carts.

Water pipelines and emergency wells should be prepared to get power from the generating sets, possibly equipped with the generating sets, which will provide enough power to start pumps and water supply during limited supplies. Fuel reserves should be sufficient for 400h, but not less than 200 hours of the generating sets working.

4. Failure risk analysis method of WSS

Most commonly used methods of risk analysis of WSS are [22], [24], [32]:

- What-if Analysis, focus on identification risks and possible consequences, method performed by expert's team.
- Process Safety, it is used to analyse the risks associated with the performance of tasks for operating the process.
- Check List – CHL, sets of questions relevant for the system safety, the following applies:
  A positive response - there is no risk
  A negative answer - there is a risk
- Preliminary Hazard Analysis – PHA, for initial identification of hazards, uses two-parameter risk matrix, point scales are used in the likelihood damage and severity.
- Hazard and Operability Studies – HAZOP, identifies deviations from the intended course of the process, deviations can cause threats to security, uses the following keywords: no, more, less, in part, on the contrary, unlike.
- Failure Mode and Effects Analysis – FMEA, Allows identification of the defect, determine their causes and assesses the impact and costs associated with them. The number of risk assessment is estimated from the formula: $r = P \cdot C \cdot O$, where P is the damage probability, C is the consequences and O is the damage detection.
- Fuzzy Risk Analysis), a method based on fuzzy logic applied in the case of having incomplete and uncertain data [32]. It can be used in conjunction with Neuro-Fuzzy Risk Analysis and Genetic Algorithm Risk Analysis, constitute basis for intelligent risk management systems.
- Methods of using GIS database, which is a system for acquiring, storing, checking, integrating, analysing, processing and data visualization. GIS can be an important part of decision support systems and water supply in risk analysis.

The most important simulation methods that can be used in the analysis of the WSS functioning, include computer simulation methods, which use the theoretical basis of known models, such as the Cross-Łobaczew method, the Ilian method, Siertkin method, the Jaresko method [30]. The most popular programs used in the country for the calculation and analysis of the water supply network are: EPANET2 (USEPA), PICCOLO (from Safaga), WaterCAD (Heasted company currently Methods Bentley Systems), MikeNET/MakieURBAN (DHI Group), InfoWorks WS (company Walingford), InfoWater H2ONET/H2OMAP (MHW's Soft USA), ISYDYW (K. Knapik, Cracow University of Technology), WATER (T. Nidelińska Computer Services, Gliwice), Monte Carlo simulation methods.

For the management of water supply systems and their operation computer models are developed in parallel with monitoring of network systems based on a variety of systems, eg. SCADA.

5. Analysis of the reliability and safety of the water supply in emergency situations

5.1. Indicators and measurements in analysis of water distribution network

Indicators and measures that can be used in the process of WDS risk analysis generally are divided into:

- statistical - determined in accordance with accepted principles of mathematical statistics based on historical data from the operation of the subsystem,
- probabilistic - determined on the basis of the probability theory,
- linguistic - describing the risk parameters by means of the so-called linguistic variables, expressed in natural language by such words as: small, medium, large.

Key indicators, measures and functions used to estimate the individual risk parameters are [13], [33]:

- n_a - a number of failures during the analysed period of WDS operation,
- n_{aj} - a number of failures (undesirable events) caused by a specific factor *j* for the analysed period of WDS operation,
- n_{ai} - a number of failures (undesirable events) that cause a specific effect *i* for the analysed period of WDS operation,
- the average values of the number of undesirable events (failures) together with the basic statistical characteristics, such as median, standard deviation, lower and upper quartile, the degree of dispersion,
- the average operating time between failures T_p [d], which is the expected value of a random variable T_p defining operating time (ability of the system (or its components) between two consecutive failures,
- the mean repair time T_n [h] is interpreted as the expected value of time from a moment of failure to a moment when an element is included to the operation. It is the sum of the waiting for repair time T_d and the real repair time T_0 (till the inclusion of the element to the operation):

$$T_n = T_d + T_0 \tag{1}$$

The analysis of the WDS operation in terms of water consumers safety must also take into account as a component of failure repair time, the time of interruptions in water supply to customers.

The failure rate $\lambda(t)$ [number of failures·year (day)$^{-1}$] or [number of failures·km^{-1}a^{-1}] is calculated according to the formulas [13]:

$$\lambda = 1/T_p \tag{2}$$

and for linear elements:

$$\lambda(t) = n(t,t+\Delta t)/N \cdot \Delta t \tag{3}$$

where T_p = the average time between subsequent failures; $n(t, t + \Delta t)$ = total number of failures in the time interval $(t, t + \Delta t)$; N = number of analysed elements or for linear elements their length L [km]; and Δt = time of observation.

- the repair rate $\mu(t)$ [number of repairs·a(h)$^{-1}$] determines the number of failures repaired per time unit, it can be determined from the operating data according to the formula (with assumption of Poison stream of failures):

$$\mu = 1/T_n \tag{4}$$

the frequency of failures f is calculated as the average number of failures (damages, undesirable events) per time unit during the operation [failure/s, failure/month].

5.2. Method of safety integrity levels of water supply in crisis situations

According to the standard [9], [10], the requirements for reducing the risk corresponds to the level of integrity of security in accordance with the scale reduction of risk. The transition from a given level of safety integrity requires a higher level of risk reduction [3], [7]-[8], [10].

There are several methods of analysis and assessment of the risk of failure in SZZW for the safety assessment of SZZW [26], [31]-[32].

The basic definition of risk is presented by the formula:

$$r = \sum_{i=1}^{n} P_i \cdot C_i \tag{5}$$

where P_i is the occurrence probability of undesirable event of the *i-th* kind in the time unit (*i* = 1, 2, ..., n), C_i is the effects of undesirable event of the *i-th* kind in the time unit and n is the number of undesirable events.

Matrix shows the dependence of the probability of the hazard occurrence from their consequences (effects).
Risk matrix R is called the representation:

$$\{P_1, P_2, \ldots i\} \times \{C_1, C_2, \ldots j\} \ni (i,j) \rightarrow r_{ij} \in R \quad (6)$$

where P_i is the occurrence probability of undesirable events, i = 1,2, ... m, m is the number of the scale for the probability parameter, c_j is consequences - relative losses associated with a given probability, j = 1,2 ... n and n is the number of the scale for the parameter statement.

The most popular method of risk analysis is matrix method, in which to the individual parameters a weight point is assigned in appropriate scale, eg. P = 1 - small, 2 - medium, 3 - large, C = 1 - small, 2 - medium, 3 - large, in this way, a set of risk values in range < (1 to 9) is obtained. The next step is the risk assessment, in which three- or five-step scale is assumed.
In work [28] the implementation of expanded risk matrix was proposed, consisting in assigning individual estimates of probability and losses risk weight and obtain in a measurable way risk taking into account the total number of identified threats.
Research related to the risk analysis of municipal infrastructure [22] have shown that on its size beside the parameter of likelihood and losses great impact has protection parameter (O), which is inversely proportional to the size of the risk or vulnerability parameter (V) [28].
Assessment of the risk index is made on the basis of the aforementioned parameters [27]:

$$ir = f(S, P, C, V) \quad (7)$$

and

$$ir = 1/PNB \quad (8)$$

where S is the scenario of undesirable events, P is the probability of the representative scenario of undesirable event, C is the amount of losses of the occurrence of undesirable events scenario, V is the vulnerability to the of undesirable events scenario occurrence and PNB is the required safety integrity level [34].

The proposed classification of risk factors is shown in *Table 1*.

Table 1. Calibration of risk parameters

Risk parameters		Qualitative classification	Quantitative classification / Quantitative weights
Probability of hazard occurrence - P	P_1	improbable; once in > 10 years	≤ 10
	P_2	unlikely; within a range from 1 to 10 years	(10÷100)
	P_3	sporadic; once a year	≥ 100
Vulnerability - V	V_1	small vulnerability - high resistance, professional monitoring system and safety barriers	≤ 10
	V_2	high vulnerability - low resistance), limited qualitative and quantitative monitoring	> 10
The size of the possible effects - C	C_1	financial losses to $5 \cdot 10^3$ EUR	≤ 10
	C_2	slightly exceeding the normative water quality, health indisposition of consumers, consumer complaints on water quality (eg. an unpleasant odor nuisance, etc.). financial loss to 10^4 EUR	(10÷100]
	C_3	required hospitalization of exposed people, notification in the public media; financial loss to 10^5 PLN	(100÷1000]
	C_4	threat to life or health of consumers, serious toxic effects of indicator organisms, mass hospitalization, fatalities, top news in the media; financial losses over 10^5 PLN	> 1000

Table 3 presents the proposal to introduce the following safety integrity levels for the system of water supply, which is characterized by continuous operation. Three-scale safety integrity levels of *PNB 1*, *PNB 2* and *PNB 3* depending on the acceptable range of tolerable level of risk was proposed, appropriate for different categories of customers in WSS. In this way, you can analyse the various undesirable events, adopting the following categories of recipients (*Table 2*) determining the required safety categories. In *Table 2* values of demanding stationary availability index (K_{sd}) depending of different water network category were presented.

Table 2. The required values of reliability, depending on the category of the water supply system according to [40]

Water network category	The coverage ratio of total water demand Qd, %	Failure frequency C, $1 \cdot year^{-1}$	Time of renewal To, h	Ksd(WSS)
I.Particularly important industrial plants, large waterworks large number of residents > 50 000	100 Qd	≤ 3	≤ 24	≥ 0,9917809
	≥ 70 Qd	≤ 2	≤ 24	≥ 0,9945206
	> 0 Qd	≤ 0,02	≤ 24	≥ 0,9999453
II. Average waterworks number of residents 500÷50 000	100 Qd	≤ 6	≤ 24	≥ 0,9835617
	≥ 70 Qd	≤ 3	≤ 24	≥ 0,9917809
	> 0 Qd	≤ 0,02	≤ 24	≥ 0,9994542
III. Small waterworks, number of residents ≤ 500	100 Qd	≤ 12	≤ 24	≥ 0,9671233
	≥ 70 Qd	≤ 6	≤ 24	≥ 0,9835617
	> 0 Qd	≤ 1	≤ 24	≥ 0,9972603

Table 3. Proposal of safety integrity levels for WSS purposes

Parameters	Categories of recipients		
	I	II	III
Tolerable hazard risk	$[10^{-3} \div 10^{-2})$	$[10^{-2} \div 10^{-1})$	$[10^{-1} \div 10)$
	$[10^{-4} \div 10^{-3})$	$[10^{-3} \div 10^{-2})$	$[10^{-2} \div 10^{-1})$
	$[10^{-5} \div 10^{-4})$	$[10^{-4} \div 10^{-3})$	-
PNB	Risk index ir		
	I	II	III
PNB 1	[1000÷100)	[100÷10)	[10÷1/10)
PNB 2	[10000÷1000)	[1000÷100)	[100÷10)
PNB 3	[100000÷10000)	[10000÷1000)	-

Category I assumes higher level of security, eg. *PNB 3*, which defines an emergency situation occurs once every ten thousand years. The lowest level of tolerable risk is inseparably linked with the expected high level of security, and with the necessary risk reduction.

Determination of *PNB* for each undesirable event is made on the basis of parameters probability, vulnerability and magnitude the potential consequences, as proposed in the work [32].

Presented assessment can be read in the following way, eg. the level of *PNB 1* we identify with the need to apply the basic techniques of WSS operation to meet the function with respect to the required level of security, while in the case of *PNB 2* and *PNB 3* should be considered additional procedures to ensure the maintenance of a given level *PNB*.

5.3. Analysis of the water pump reliability

5.3.1. Introduction

In both normal and emergency conditions, a particular role in the water supply systems operation (except gravitational) play water supply pumping stations (WSPS), which due to their functions (supply of water in the desired quantity and at the appropriate pressure), are their neuralgic subsystems. They determine the correct operation of the entire WSS, therefore, they should have a high level of reliability. Assessment of the reliability level achieved by the system (object) can be made based on measurable, and therefore possible to compare, different measures (indicators) of reliability which can be obtained by several computational methods developed by reliability researchers. Many of them can also be applied to assess the expected performance level imposed on water supply pumping stations. These methods are more or less complicated and laborious, but also give more or less accurate estimation of the level of reliability. The most popular methods are, among others: analytical, based on reliability schemes donating in a simplified way real solutions of these objects (how to connect the pumps and pipelines), a complete inspection, partial inspection, fault tree (functors), paths and cuts, the minimum cross-sections failures, queuing theory, Monte-Carlo, and others described by numerous national and foreign authors of which mentioned here are only exemplary ones [1], [2], [4]-[5], [13]-[14], [16]-[17], [19], [39]. Among these methods particularly effective method seems to be minimal cut set failure (MCSF) in a version modified by J. Gumiński [6]. It is suitable for the study of complex technical systems (objects) such as WSPS. This method provides full information on reliability of the examined object (based on this method three important indicators of the reliability of the system can be determined: the average working time between failures T_{ps}, mean time of repair T_{ns} and binding these two measures the so-called stationary availability index K_s, with a relatively moderate effort [2]. Below the theoretical basis was described and a methodical example explaining the course of conducting analysis of reliability was given.

5.3.2. The theoretical basis of the minimal cut set failure method

Method of minimal cut set failure belongs to the group of methods based on the structural and functional analysis and generally involves the identification of the so-called reliability structure of the examined system. This identification is based on an analysis of the possible flow paths (e.g. water), performed taking into account the fulfilment of system function. Reliability structure of the system determines the relationship between reliability states of elements (functional or damaged), and the state of the system reliability. Therefore**,** by the term of flow path or equivalent - path of system efficiency – one should understand such set of system components whose efficiency determines the efficiency of the system, regardless of the condition of the other elements. The flow way (path) is called minimum when there are no other way as a subset, and thus it is formed by the minimal set of elements whose efficiency ensures the system operation. In a logical sense, the set is a conjunction indicating that elements of the minimum flow path (MFP) form a serial reliability structure. Minimum number of flow paths in the system is determined by its technical structure and assumed criterion of efficiency, and their set creates a parallel structure (in terms of logic, it corresponds to an alternative), because only one of them is enough to make the system operational. Efficiency criterion is defined by technical and technological requirements of the system in normal and emergency conditions (e.g. the nominal and minimum acceptable efficiency). The designation of all the minimum flow paths allows to specify the so-called minimal cut set failure (MCSF): single-, double-, triple- or more elemental, depending on the desired accuracy of the calculations. Single cut set failure element is the element whose failure causes the break of all the flow paths in the system. It is therefore the element that repeats itself in all the flow paths. Such cut set failure element may be one, more than one, or they may not appear at all. If there are some elements, they all form a set of one-elemental minimal cut set failure. Two-elements of cut set failure form a pair of elements whose simultaneous failures cause break of all the flow paths and therefore the system goes to a disabled state.

The elements that constitute a one-elemental cut set failure are not considered. In a similar way, you can determine the three-, four-, and more elemental cut set failure.

To determine the minimal cut set failure a two-dimensional matrix of zero-one is build (number of minimum ways x number of system elements), in which a logical one ("1") describes all the efficient elements, forming flow path, and the elements whose efficiency in a given way is not necessary are described by a logical zero ("0").

If in a column of matrix treated as column vector are only ones, then the element forms a one elemental cut set failure. After eliminating all such vectors a new matrix of reduced size is formed. In turn, those two column vectors are sought, whose logical sum provides a vector built only of ones. In this way, a set of two-elemental cut set failure is determined.

Similarly, the threes of elements forming the three-elemental cut set failure are sought, but those of them which contain previously designated one- and two-elemental cut set failure are not considered. In the same way further cut sets are determined : four- or more elemental cut set failure , checking each time that each of the designated, generally N-elemental cut set failure does not contain in itself previously designated 1, 2, 3, ... N-1 elemental cut set failure sections.

In practical applications of this method, consideration are usually limited to designate a maximum of three, and even a two-elemental cut set failure, since the probability of simultaneous damage to a greater number of elements of the system, compared to their typically high reliability, is very little. It allows a significant simplification of the calculations with making a minor error. Such procedure, however, cannot be the rule, which should be kept in mind during reliability analysis and when making decision concerning the degree of simplification.

5.3.3. Simplifying assumptions and basic calculation formulas

After determination of the minimal cut set failure, you can assess the reliability of the system using the formulas used in the two-parameter method of assessing the reliability of systems with serial and parallel structure, based on the concept of failure frequency [39]. They were derived while complying the assumption that the state of each system elements are described by independent, stationary, ordinary and ergodic random process, that the distributions of time between failures (T_p) and time to repair (T_n) are exponential. In the case of the MCSF method it is additionally assumed that, in relation to the occurrence of minimal cut set failure the separability rule is applied. It assumes that the system failure can occur only during one of cut set failure (the simultaneous appearance of two or more number of cut set failure is excluded).

The assumptions allow to note the system failure rate (Λ_s) as the sum of the failure rate of individual minimal cut set failure: single, double, triple, generally N-elemental:

$$\Lambda_S = \sum_{i=1}^{M_1} \lambda_i^{(1)} + \sum_{j=1}^{M_2} \lambda_j^{(2)} + \sum_{l=1}^{M_3} \lambda_l^{(3)} + \ldots + \sum_{\alpha=1}^{M_0} \lambda_\alpha^{(N)} \qquad (9)$$

where $\lambda_i^{(1)}$ is the failure intensity of *i*-th one elemental cut set failure [1/h]; $\lambda_i^{(1)} = \lambda_i$, λ_i –

failure intensity of element, $\lambda_j^{(2)}$ - failure intensity of *j*-th two-elemental cut cross failure [1/h], $\lambda_l^{(3)}$ – failure intensity of *l*-th three-elemental cut set failure [1/h], $\lambda_\alpha^{(N)}$ – failure intensity of α-th N-elemental cut set failure [1/h], M_1, M_2, M_3, M_0 – number of cut set failure, respectively: one-, two-, three-, N-elemental.

Values of $\lambda_i^{(1)}$ refer to the single elements, which are one elemental cut set of system failure. They are defined from the formula (2) given in point 4. The values are calculated on the basis of the statistics or are taken from the literature, and the values $\lambda_j^{(2)}$, $\lambda_l^{(3)}$, ..., $\lambda_\alpha^{(N)}$ are calculated from the proper formulas (such as for the parallel structures) [29], [39]. Limiting further considerations in this paper for single and two-elemental cut set failure, the failure intensity of the latter can be written as follows:

$$\lambda_j^{(2)} = \frac{\lambda_{j1} \cdot \lambda_{j2} \cdot (Tn_{j1} + Tn_{j2})}{1 + \lambda_{j1} \cdot Tn_{j1} + \lambda_{j2} \cdot Tn_{j2}} \cong \cong \lambda_{j1} \cdot \lambda_{j2} \cdot (Tn_{j1} + Tn_{j2}) \quad (10)$$

where $\lambda_j^{(2)}$ as in equation (9), λ_{j1}, λ_{j2} is the failure intensity of the first and the second element in *j*-th two-elemental cut set failure, T_{nj1}, T_{nj2} - the average repair times of the first and the second element in the *j*-th two-elemental cut set failure. The mean time of system repair is:

$$Tn_S \cong \frac{\sum_{i=1}^{M_1} \lambda_i^{(1)} \cdot Tn_i^{(1)} + \sum_{j=1}^{M_2} \lambda_j^{(2)} \cdot Tn_j^{(2)}}{\Lambda_S} \quad (11)$$

where $Tn_i^{(1)}$, $Tn_j^{(2)}$ is an average durations of repair respectively *i*-th one-elemental and *j*-th two-elemental cut set failure [h].
Values of $Tn_i^{(1)}$, as $\lambda_i^{(1)}$, for the one-elemental cut set are calculated on the basis of operational data, and two-elemental cut set uses the following formula for the mean time of repair of two-elemental parallel structure [29], [39]:

$$Tn_j^{(2)} = \frac{Tn_{j1} \cdot Tn_{j2}}{Tn_{j1} + Tn_{j2}} \quad (12)$$

where Tn_{j1}, Tn_{j2} as in the equation (10).

With values Λ_s and Tn_s the other reliability indicators can be calculated, i.e. the average failure free time in the system (Tp_s) and stationary availability index (K_s), according to the practical applications of reliability theory [39]:

$$Tp_S = \frac{1}{\Lambda_S} \quad (13)$$

$$K_S = \frac{Tp_S}{Tp_S + Tn_S} \quad (14)$$

5.3.4. Methodical example of the WSPS reliability analysis using MCSF method

To familiarize the conduct of reliability assessment using the method of minimal cut set failure, and especially structural analysis method, a methodical example was provided. For the considered complex system, for which reliability indicators T_{ps}, T_{ns} and K_s are searched, water supply pumping station with two main discharge collectors (MDC) was adopted, which is schematically shown in *Figure 1*.
It was assumed that, for its full efficiency, the work of two out of four installed pumping units and at least one MDC is enough.

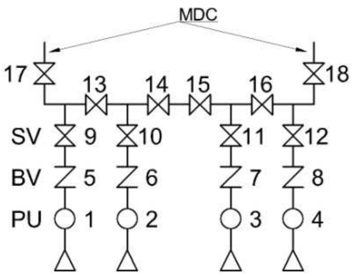
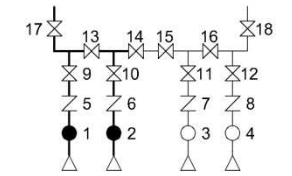
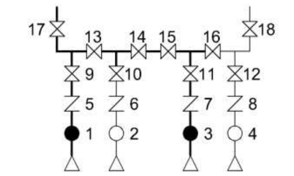
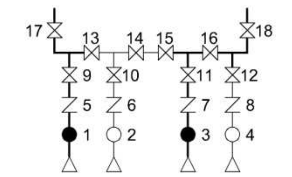
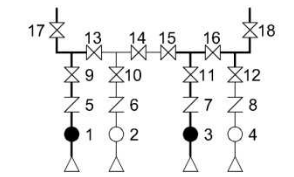
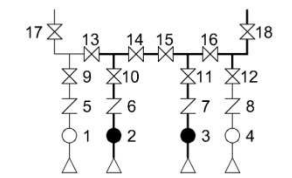
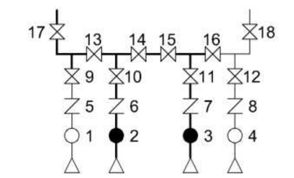
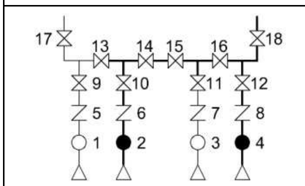
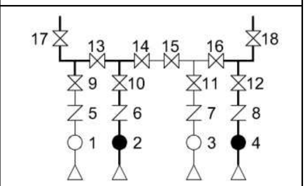
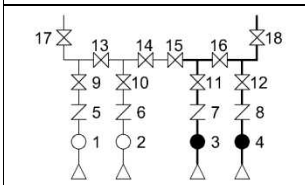


Figure 1. Technical scheme of the analyzed water pumping station: PU - pumping unit, BV - backflow valve, SV - stop valve on the discharge pipe (collector) (discharge gate), MDC - the main discharge collector, 1,2, ..., 18 - numbers of pumping station elements

Conducting the reliability assessment of analysed pumping station is preceded by determining the set of minimum efficiency paths (minimum flow paths), and then, on this basis, the minimal cut set-failure. In this case, the number of possible flow paths is determined by the number of working and backup pump units, the number and piping placement, valves and backflow valves and structures of these elements connection.
Designated minimum paths, represented by the numbers of elements that build them with their graphic illustration (bold lines) are given in *Table 4*.
Each minimum path constitutes a set of elements, whose efficiency is enough for the realization of pumping function, defined here only by the criterion of capacity ($Q = Q_n$; Q_n - nominal capacity). In the presented case it is fulfilled during the work of the two pumping units and the possibility to transmit water by at least one main discharge collector.

Table 4. The designation of MFW for the analysed WSPS

Graphic illustration of Minimum Flow Way (MFW)	
MFW1	MFW2
	
Symbolic record of considered MFW	
MFW1	1,2,3,_,_,6,7,8,_,_,11,12,13,_,_,16,17,18
MFW2	1,2,3,_,_,6,7,8,_,_,11,12,13,14,15,16,17,18
Graphic illustration of Minimum Flow Way (MFW)	
MFW3	MFW4
	
Symbolic record of considered MFW	
MFW3	1,2,3,_,_,6,7,8,_,_,11,12,13,_,_,16,17,18
MFW4	1,2,3,_,_,6,7,8,_,_,11,12,13,14,15,16,17,18
Graphic illustration of Minimum Flow Way (MFW)	
MFW5	MFW6
	
Symbolic record of considered MFW	
MFW5	1,2,3,_,_,6,7,8,_,_,11,12,13,_,_,16,17,18
MFW6	1,2,3,_,_,6,7,8,_,_,11,12,13,14,15,16,17,18
Graphic illustration of Minimum Flow Way (MFW)	
MFW7	MFW8
	
Symbolic record of considered MFW	
MFW7	1,2,3,_,_,6,7,8,_,_,11,12,13,_,_,16,17,18
MFW8	1,2,3,_,_,6,7,8,_,_,11,12,13,14,15,16,17,18
Graphic illustration of Minimum Flow Way (MFW)	
	
Symbolic record of considered MFW	
MFW9	1,2,3,_,_,6,7,8,_,_,11,12,13,14,15,16,17,18

Particular minimal paths are, therefore, both elements appearing in the water flow path in the given configuration of working pump units, as well as elements "separating" the rest of the pumping station not participating in the transport of water.

Designated minimum paths are then recorded (in the numerical order given in *Table 4*) in the form of zero-one matrix (*Table 5*), illustrating the coded record of reliability structure of pumping station . This matrix, as discussed in point 5.3.2, allows to determine the individual MCSF, in this example the consideration was limited to one- and two-elemental cut set .

Analysing *Table 5* it can be seen that none of the column vectors contains only ones, and therefore there is no one-elemental cut set.

It means that none of the components of analysed WSPS will cause lack of the ability to meet its functions (with the criterion of efficiency).

Table 5. MFW recording in matrix 0-1

Pumping station elements																	
Pumping unit (PU)				Backflow valve (BV)				Stop valve (SV) on:									
								Discharge pipeline				Aggregate collector				MDC	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	0
1	0	1	0	1	0	1	0	1	1	1	0	1	1	1	1	1	0
1	0	1	0	1	0	1	0	1	0	1	1	1	0	1	1	1	1
1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	1
0	1	1	0	0	1	1	0	0	1	1	1	1	1	1	1	0	1
0	1	1	0	0	1	1	0	1	1	1	0	1	1	1	1	1	0
0	1	0	1	0	1	0	1	0	1	1	1	1	1	1	1	0	1
0	1	0	1	0	1	0	1	1	1	0	1	1	1	0	1	1	1
0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	1

Table 6. The designation of MCSF for the analysed WSPS

1-el. the minimal cut set failure : M1 = 0		
2-el. the minimal cut set failure : M2 = 29		
Type [PU, SV]	Type [BV, SV]	Type [SV, SV]
[1,16], [2,16], [3,13], [4,13]	[5,16], [6,16], [7,13], [8,13]	[9,11], [9,12], [9,15], [9,16], [9,18], [10,12], [10,16], 10,18], [11,13], [11,17], [12,13], [12,14],[12,17], [13,15], [13,16], [13,18], [14,16], [14,18], [15,17], [16,17], [17,18]
M2 (PU, SV) = 4	M2 (BV, SV) = 4	M2 (SV, SV) = 21

Such conditions occur when simultaneously pump units and some fittings (among stop valves) are in failure state and when only the fittings elements (some of the valves with valves and backflow valves with some valves) are in failure state.

In the zero-one matrix logical sum of column vectors, corresponding to such two simultaneously damaged elements, provide vectors constructed with only ones. Obtained in the analysis minimum cut set failure are summarized in *Table 6*. For them, using the previously given relations, the calculation is performed of the relevant reliability parameters ($\lambda_j^{(2)}$, $T_{nj}^{(2)}$) and system indicators (Λ_s, Tp_s, Tn_s and K_s).

6. Conclusion

The management of risk connected with the WSS 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, which means to choose the best alternative which will assure them the best results in their economic activity.

WSS exploitation in terms of belonging to a critical infrastructure is an important issue and requires a detailed analysis. Therefore it is important to develop emergency plans for the supply of drinking water for different crisis situations, as well as detailed analysis of the risk of possible undesirable events in WSS, in order to develop a comprehensive safety management program of the system.

The development of appropriate risk assessment methods for WSS in crisis situations reduces the potential consequences of an accident, helps in taking decisions by engineers, designers and government officials regarding the selection of the optimal solution, as well as methods to protect WSS consumers and the surrounding environment from the negative effects. Analysis of the risks associated with the operation of WSS will help to increase the safety of consumers, which should be the standard in the management of water supply systems. It is also important in the implementation of sustainable development principles in the management of water supply. The universality of the presented methods and the possibility to use them in the evaluation of various WSS characterized by a different specificity should be emphasized.

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