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Analysis of risk and failure scenarios in water supply system

Keywords

fault tree analysis, matrix methods, risk analysis, water supply system

Abstract

Water supply system is complicated technical system which belongs to underground urban infrastructure. Its accurate functioning determines everyday live stability of citizens. Risk analysis is a key phase of the process of water supply safety management. The aim of this paper is to present new propose of methods for risk of the first type (associated with quantity of supplied water) and the risk of the second type (associated with quality of supplied water) analyses in water supply system. The paper contains the description of matrix methods for risk analyses and methods describing cause-and-effect relationship of failure events (fault tree analysis).

1. Introduction

A first, intuitive observation comes from the fact that there is risk if there exists a potential source of damage, or hazard. When a hazard exists, e.g. posed by a system which in certain conditions may cause undesired consequences, safeguards are typically devised to prevent the occurrence of such hazardous conditions and its associated undesired consequences [22].

Technical systems are structurally very complex, and they often have complicated operation processes. Large numbers of components and subsystems and their operating complexity make the evaluation and prediction of their reliability, availability, and safety difficult. The time dependent interactions between the systems' operation processes, changing of operation states and the systems' structures and their component reliability and the changing of safety states and processes are evident features of most real technical systems [10].

Water supply system (WSS) is characterised 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 objective realities in WSS operating are the losses caused by the breaks in water supply or the low quality of supplied water [11]-[12]. The related risk can rise protests of drinking water consumers. Nowadays the water-pipe companies try to get quality management certificates according to the international standard ISO 9001:2000 or others [1], that requires the procedures to estimate widely understood risk.

Etymology of the word risk has multiaspects meaning. In Arabic risq means fate, act of God. In Spanish ar-risko means courage, danger. In English, however, the synonym of risk is the word hazard that is understood as danger or a potential source of danger. In Greek riza means sharp cliff, reef. In Latin riscare means to dodge something. P.L. Bernstein in his work [3] says that risk comes from an old Italian word risicare which means to have courage to do something. 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 [4]-[5], [19], [21].

The basic measure describing WSS safety is risk [16] and the elaboration of the model to analyse risk connected with WSS operating including the impact of the domino effect will allow to use the safety barriers properly. The safety barriers are following:
- control and measuring barrier. When the boundary values of technological parameters are exceeded the control functions are activated. If the control system succeeds the conditions for normal operation are restored. If this barrier fails the potential of threat occurs and it activates the next safety barrier.
- alarm barrier. The second barrier activates e.g. warning signs, certain alarms to which the WSS operator should respond. As a rule its operating is connected with all kinds of blockades which leads to the stoppage of water production. If the operation of this blockade is not taken into consideration or is neglected the direct threat for WSS users (drinking water consumers) arises.
- rescue scenarios barrier. The third kind of barrier is already connected with the activation of the rescue scenarios and procedures that reduce the consequences of failure. If these procedures fail or are not effective enough it leads to the global losses which in a case of WSS can be accompanied by people gastric problems and, in the critical situations, lethal outcome. In this sense we can talk about the early, delayed and late warning safety barriers.

The main aim of this paper is to present new propose of methods for risk analysis in WSS.

The paper contains the description of matrix methods and fault tree analysis. The risk analysis of the first type and the risk analysis of the second type in WSS was proposed.

2. Failure events in water supply system

Unreliability, as a measure of the probability that the system does not meet its intended functions, does not include neither the consequences of such a failure [2], [7] nor the effect of the sequential occurrence of basic events on such a failure. Failure is defined as the event in which the system fails to function with respect to its desired objectives. Failure can be grouped into either structural failure or performance failure [19]:

- Raw water system:
  - event: Contaminated water in source,
  - causes: biological contamination, chemical contamination,
  - consequences: Contaminated water enters water treatment system.
- Water treatment system:
  - event: Primary contamination,
  - causes: an early warning system did not detect contamination, monitoring in Water Treatment Station did not detect contamination, no alternative treatment technology is run,
  - consequences: Contaminated water enters water distribution system.
- Water distribution system (WDS):
  - event: lack of water or contaminated water delivered to consumer,
  - causes: failures in water pipes, secondary water contamination in water-pipe network, primary contamination,
  - consequences: lack or breaks of water supply to consumers, threat to consumers health due to consumption of poor quality water, financial losses in waterworks, as a result of loss of water supply service, and of repairs (washing the network, unsold water or compensations for water consumers, financial losses of consumers caused by the purchase of bottled water).

Different failure-modes may be identified in the water-pipe network such as:

- loss of integrity of the water pipe,
- loss of integrity of the connectors or the expansion units,
- loss of fittings (gates, valves, hydrants, vents and drains),
- wrong design of the structure of the water-pipe network,
- miss-matching of hydraulic conditions to the network (too high working pressure, lack of fittings protecting against hydraulic impacts),
- loss of thickness of the pipes by corrosion (corrosive ground medium).

These failure modes may be associated to one or more of the following failure mechanisms:

- ground corrosion,
- thermal fatigue (temperature changes: cyclic/randum),
- mechanical fatigue (vibration: cyclic/random),
- human intervention.

Failures result from the combined action of time, excessive stress and/or local unfavourable environmental conditions.

The failures in water-pipe network depend also on the material of the network:

- in gray cast iron networks: the loss of tightness of joints and mechanical damages are frequent,
- in steel networks: loss of thickness by corrosion, welds cracking, and mechanical damages are frequent,
- in plastic network: connection leak and mechanical damages are frequent.

The main mechanisms causing secondary pollution of water in the water-pipe network include [17]:

- corrosion and oxidization (susceptibility of the material of the pipes),

- significant changes in speed of flow (sludge is washed out),
- low speed of water (stagnant water in water pipes, the increase in water temperature),
- rapid change in pressure resulting in local vacuum (sludge is washed out),
- poor technical and sanitary condition of pipes (corrosion of pipes, a large quantity of bio-film, pipes leak),
- corrosion caused by aggressive water,
- lack of chemical instability of the water,
- inappropriate water treatment process (causing chemical instability of water in network),
- high doses of unused disinfectant remain in water (an increase of corrosion),
- accumulation of sludge in the network,
- presence of biochemical processes in the network,
- contamination of the network during repairs, replacement of pipes and fittings (the possibility that pollutants from the ground will pass into water in water-pipe network),
- household and industrial devices directly connected to the network (pollution from the installation is sucked into water-pipe network).

3. General characteristic of matrix methods for risk assessment in WSS

Procedures for risk analysis cover the whole activity aiming to identify threats, to estimate risk and its size. The appearance of the extraordinary event produces the state of emergency to which some potential of danger is assigned. The release of this potential leads to failure and failure related losses (financial) and even to the loss of health and human death. Determination of the acceptable risk level relies on an introduction of the criteria values according to the rules given in *Figure 1*.

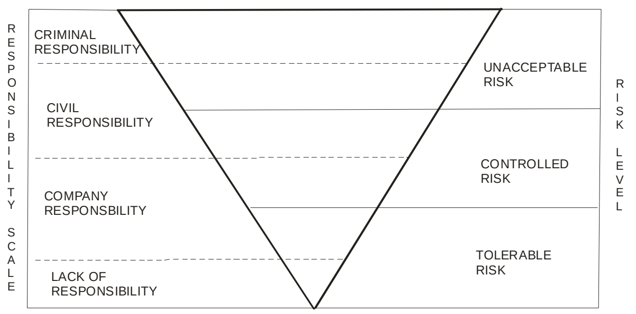

Figure 1. The illustration of the possibilities that the given risk level occurs [14]

As an example we can suggest to introduce the following categories of probability – frequency of the undesirable events occurrence and the categories of their consequences, presented in *Table 1*.

Table 1. Probability and consequences for matrix method [14]

Probability (frequency)		Consequences	
X_1	Often	Y_1	Catastrophic
X_2	Probable	Y_2	Serious
X_3	Occasional	Y_3	Significant
X_4	Little probability	Y_4	Marginal
X_5	Improbable	Y_5	Negligible

Each time risk (r) is determined according to the formula:

$$r = X \times Y \tag{1}$$

where:
X – frequency of the undesirable events occurrence,
Y – consequences of the undesirable events.
Using the formula (1) we can obtain the following possibilities of the undesirable events combinations shown as the risk matrix below.

$$M_R = |X_i \times Y_j| = \begin{vmatrix} X_1{\times}Y_1 & X_1{\times}Y_2 & X_1{\times}Y_3 & X_1{\times}Y_4 & X_1{\times}Y_5 \\ X_2{\times}Y_1 & X_2{\times}Y_2 & X_2{\times}Y_3 & X_2{\times}Y_4 & X_2{\times}Y_5 \\ X_3{\times}Y_1 & X_3{\times}Y_2 & X_3{\times}Y_3 & X_3{\times}Y_4 & X_3{\times}Y_5 \\ X_4{\times}Y_1 & X_4{\times}Y_2 & X_4{\times}Y_3 & X_4{\times}Y_4 & X_4{\times}Y_5 \\ X_5{\times}Y_1 & X_5{\times}Y_2 & X_5{\times}Y_3 & X_5{\times}Y_4 & X_5{\times}Y_5 \end{vmatrix}$$

- the unacceptable risk $R_U = [X_1{\times}Y_1,\ X_1{\times}Y_2,\ X_1{\times}Y_3,\ X_2{\times}Y_1,\ X_2{\times}Y_2,\ X_3{\times}Y_1]$
- the controlled risk $R_C = [X_1{\times}Y_4,\ X_1{\times}Y_5,\ X_2{\times}Y_3,\ X_2{\times}Y_4,\ X_3{\times}Y_2,\ X_3{\times}Y_3,\ X_4{\times}Y_1,\ X_4{\times}Y_2,\ X_5{\times}Y_1]$
- the tolerable risk $R_T = [X_2{\times}Y_5,\ X_3{\times}Y_4,\ X_3{\times}Y_5,\ X_4{\times}Y_3,\ X_4{\times}Y_4,\ X_4{\times}Y_5,\ X_5{\times}Y_2,\ X_5{\times}Y_3,\ X_5{\times}Y_4,\ X_5{\times}Y_5]$.

The procedure presented above gives a general characteristic of the essence of matrix methods for risk assessment. The risk matrix presented as the risk matrix has a character of matrix to which the undesirable events are referred.
Water-pipe network is expanded technical system and its reliable operation depends on many internal factors (structure, material, conditions of hydraulic flow) [20] as well as on external factors (ground and climatic conditions, outside activity of man). Consequences resulting from the impact of these factors are failure events causing unreliability of the entire or part of WSS, which in consequence may lead to a loss of water consumers safety, that should be considered in two aspects: threats resulting from the lack of water or interruption in the supply of water and threats resulting from the possibility of consuming contaminated water (which may cause the loss of life or health of consumers) [13].
Safety of WSS is defined as all conditions and actions that must be met at all stages of water production and supply, in order to ensure health benefits for humans. In light of the applicable law,

the manufacturer - water supply company, is responsible for water health quality.

According to [9] risk is interpreted as a set of the products of probabilities (P_n) and consequences (C_n):

$$r = \{P_1 \times C_1, P_2 \times C_2, \ldots, P_n \times C_n\} \quad (2)$$

Risk assessment is a procedure that consists of:

- hazard identification,
- assessment of the probability of threat occurrence,
- assessment of the vulnerability to threat,
- consequence analysis.

The definition of water consumer risk takes into account the following parameters:

- measure of the probability (P) of undesirable events in WSS that are directly felt by water consumers,
- related losses (C) (e.g. purchase of bottled water, possible medical expenses after consuming non-potable water or immeasurable losses, such as municipal and economic difficulties and loss of life or health),
- degree of vulnerability (V) to events.

Consumer's risk is:

$$r_C = r_{CI} + r_{CII} \quad (3)$$

where:

r_C – the consumer's risk,

r_{CI} – the risk of the first type, associated with quantity of supplied water,

r_{CII} – the risk of the second type , associated with quality of supplied water.

For the risk of the first type, associated with quantity of supplied water, and for the risk of the second type, associated with quality of supplied water, the three parametric definition was assumed [18]:

$$r_{CI,II} = \sum_{RS=1}^{N} (P_{iI,II} \times C_{jI,II} \times V_{kI,II}) \quad (4)$$

where:

RS – a sequence of consecutive undesirable events or a single undesirable event that may cause the risk of the first type or the risk of the second type (RS - representative scenario),

$P_{iI,II}$ – probability of the RS occurrence or a single event that may cause the risk of the first type or the risk of the second type,

$C_{jI,II}$ – losses caused by the given RS or a single undesirable event that may cause the risk of the first type or the risk of the second type,

$V_{kI,II}$ – vulneralibility associated with the occurrence of the given RS or a single undesirable event that may cause the risk of the first type or the risk of the second type,

N – a number of RS or single undesirable event.

The following point (PW – point weight) and descriptive scale for the particular risk parameters, according to *Tables 2-4* was proposed (for the risk of the first type). The criteria presented below were developed on the basis of own research and study of literature [6], [8], [16].

Table 2. Criteria of point and descriptive scale for the parameter P_{iI}, $i = \{1,2,3,4,5\}$

PW	Description of the parameter *P*	Ranges of probability of undesirable event occurrence *P*
1	very low probability	once in 10 years
2	low probability	once in 5 years
3	medium probability	once in 2 years
4	high probability	once in 0.5 years
5	very high probability	once a month and more often

Table 3. Criteria of point and descriptive scale for the parameter C_{jI}, $j = \{1,2,3,4,5\}$

PW	Description of the parameter *C*
1	Very small losses: - local drop of water pressure in water-pipe network, - breaks in water supply to consumers on higher floors,
2	Small losses: - drop of daily water production (Q_{dmax}) up to 70% of the nominal water production (Q_n), or interruptions in water supply up to 2 h, - isolated consumers complaints.
3	Medium losses: - Q_{dmax} = <50÷70) % Q_n or interruptions in water supply up to (2÷12> h for individual consumers, - drop of water pressure in water-pipe network, - financial losses.
4	Large losses: - Q_{dmax} = <30÷50) % Q_n or interruptions in water supply up to (2÷12> h for individual consumers, - drop of water pressure in water-pipe network, - financial losses.
5	Very large losses: - Q_{dmax} < 30% Q_n , drop of water pressure in water-pipe network, - failure in mains water supply, interruptions in water supply >24 h for particular housing estates, districts or a whole city, - considerable financial and social losses.

The risk of the second type criteria for the probability parameter and vulnerability parameter were assumed in the same way as for the risk of the first type risk (*Table 2*, *Table 4*).

The point and descriptive scale for the parameter C is shown in *Table 5*. The criteria presented below were developed on the basis of own research and study of literature [1], [8], [13], [15].

Table 4. Criteria of point and descriptive scale for the parameter V_{kI}, $k = \{1,2,3,4,5\}$

PW	Description of the parameter *V*
1	Very low vulnerability to failure (very high resistance): - the network in the closed system, the ability to cut off the damaged section of the network (in order to repair it) - the ability to avoid interruptions in water supply to customers, full monitoring of water-pipe network (continuous measurements of pressure and flow rate at strategic points of the network) covering the entire area of water supply, utilising Supervisory Control And Data Acquisition (SCADA) and Geographic Information System (GIS) software, the possibility to remote control of network hydraulic parameters, - emergency reserve in network water tanks covering the needs of the city for at least 24 h, (Q_{dmax} or $Q_{d.avg}$ – daily average water production), - comprehensive system of emergency warning and response, - full use of alternative water sources.
2	Low vulnerability to failure (high resistance): - the network in the closed or mixed system, the ability to cut off the damaged section of the network (in order to repair it), - standard monitoring of water-pipe network (continuous measurements of pressure and flow rate) - early warning system, - use of alternative water sources
3	Medium vulnerability to failure (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-pipe network standard monitoring, measurements of pressure and flow rate, - delayed emergency response system, - alternative water sources do not cover the needs completely.
4	High vulnerability to failure (low resistance): - 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, - limited water-pipe network monitoring, - delayed emergency response system, - limited access to alternative water sources.
5	Very high vulnerability to failure (very low resistance): - 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-pipe network monitoring, - lack of emergency warning and response system - very limited access to alternative water sources.

Table 5. Criteria of point and descriptive scale for the parameter C_{kII}, $k = \{1,2,3,4,5\}$

PW	Description of the parameter *C*
1	Very small threat: - local deterioration of water quality, - perceptible organoleptic changes of water (odour, changed colour and turbidity), but there is minimal threat to further water quality deterioration, - individual water consumers complaints, - lack of threat for consumers health.
2	Small threat: - local deterioration of water quality, - perceptible organoleptic changes of water (odour, changed colour and turbidity), but there is minimal threat to further water quality deterioration, - water consumers complaints, - lack of threat for consumers health.
3	Medium threat: - considerable organoleptic problems (odour, changed colour and turbidity) - numerous complaints, - information in local media, - threat to consumers health (the normative values for microbiological and/or physiochemical indicators are exceeded, lack of pathogenic microorganisms).
4	Large threat: - secondary water contamination in part of water-pipe network, - possibility that a large group of consumers will be exposed to consume poor quality water, - information in local media consumer's health indisposition, - the impact of the domino effect (the normative values for microbiological and/or physiochemical indicators are exceeded, lack of pathogenic microorganisms).
5	Very large threat: - secondary water contamination in water-pipe network, - possibility that a large group of consumers will be exposed to consume poor quality water, - professional emergency services are involved, - test results for indicator organisms reveal high levels of toxic substances, - information in national media, physiochemical indicators and/or pathogenic microorganisms are exceeded, - exposed people need hospitalisation.

In this way the possible values of the risk of the first type or the risk of the second type were calculated, according to formula (4), for a single RS the risk takes values in the range 1÷27. The criteria for risk assessment are as follows:

- negligible <1÷9>,
- tolerable (9÷20>,
- controlled (20÷45>,
- unacceptable (45÷60>,
- inadmissible (60÷125>.

4. The fault tree method

Fault Tree Analysis (FTA) presents graphic relations between the events influencing the occurrence of a specific undesirable event called "the pick event". Creating the tree we use the so called functors (logical gates) which determine, among others, events logical product and events logical sum.
An example of the application of the fault tree analysis in order to analyse pumping station elements (*Figure 2*) cause-effect relationship.

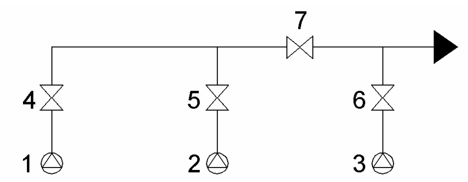

Figure 2. Pumping station

Pumping station is working if 2 of 3 pumps run. Fault tree for presented pumping station is presented in *Figure 3*.

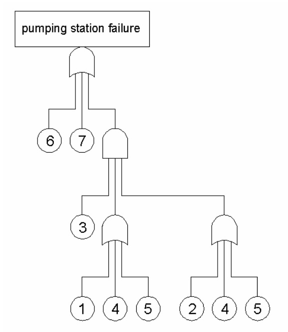

Figure 3. Fault tree for pumping station

The are two minimal cut sets:
- failure of value 6,
- failure of value 7.

Other cut sets have two or more elements. Probability of its occurrence is very low.

5. Conclusions

The matrix methods are used when exact risk measures for WSS are needed. For example if specific WSS is analyzed in case of RS occurrence:
- associated with quantity of supplied water:

very high probability of undesirable event occurrence (P = 5); large losses (C = 4), medium vulnerability to failure (medium resistance) (V = 3); r_{CI} = 5×4×3 = 60 (unacceptable risk of first type),
- associated with quality of supplied water:

low probability of undesirable event occurrence (P = 2); medium threat (C = 3), high vulnerability to failure (low resistance): (V = 4); r_{CII} = 2×3×4 = 24 (controlled risk of first type).
The fault tree method used cause-and-effect relationship of failure events. In addition, if probability values for basic events are known, probability of top event in fault tree can be establish.
Presented methods may be used in any WSS to calculate risk measures or to analyse failure scenarios. Fault tree analysis is particularly useful for the analysis of complex technical systems in which analysis of failure scenarios is a difficult process because it requires to examine a high number of cause-effect relationship. Undoubtedly the WSS belongs to such systems.

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