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Failure risk analysis in the collective water supply systems in crisis situations

Keywords

collective water supply system, crisis situation, critical infrastructure

Abstract

Risk is a basic category to estimate water supply system safety. The first step in risk assessment is to identify the threats and their possible consequences. One of methods for risk assessment is the method using the so-called risk graphs. It relies on the preliminary analysis of such risk factors as: the frequency of threat occurrence - F, the duration of the risk exposure - E, the size of the possible consequences - C and a degree of protection - O, that is inversely proportional to the mentioned measures of risk. The route along the branches of the risk graph should be started from the determination of the initiating/peak event which is the undesirable event (e.g. secondary water contamination in water-pipe network). The expanded risk graph presented in the work differs from the standard (commonly used) graph because it takes into consideration all combinations of the particular risk factors.

1. Introduction

Collective water supply systems belong to the so-called critical infrastructure of countries, regions or urban areas (in addition to such systems as power systems, telecommunication, transport, economic), which means that they are the key systems for the safety of the state and its citizens, and, in particular, local communities. The result of the existence of the various risks that may cause disruption in the supply of drinking water for a long time is called water supply crisis, which would require to run local and national emergency systems. Crisis situations can have different causes and their consequences affect the inhabitants of towns and villages. The consequences of threats can be local, regional or national. The ISO has made a decision on the development of standards that can be used by water companies in collective water supply systems safety management [ISO TC 223, ISO PAS 22399, ISO TC 224/WG 7]. In October 2007 the International Water Association (IWA) in agreement with the Israeli Authority for Standardization developed the guidelines for waterworks management in a case of crisis situations. The guidelines cover the issues relating to the various stages of management of the so-called water crisis [21].

The undertaken research problem meets the world trends on security in widely understood water management. The World Health Organization (WHO) in the third edition of the Guidelines for Drinking-Water Quality presented the first assumptions to develop Water Safety Plans (WSP) (relating mainly to protect water consumers health), however a new approach is Water Cycle Safety Plans (WCSP), which should also take into account the assessment of the risks to the environment and include CWSS studies in different situations, especially in crisis situations [23], [24], [25]. These plans should be based on risk analyses and assessments and refer to the analysis of the CWSS safety with regard to the functioning of other systems included in the widely understood water management.

The most important legal regulations concerning CWSS safety are the guidelines of the WHO and the so-called Water Framework Directive [23]. The most important national regulations are the Water Act on collective water supply and sewage disposal and the Regulation of Health Minister on the quality of water intended for human consumption. In Polish law the requirements for the CWSS functioning in crisis situations can be found in the expired regulation of the Minister of Spatial Economy and Construction regarding the principles of ensuring functioning public water supply facilities in special conditions. According to the above guidelines in crisis situation water company should: increase the dose of disinfectant, turn to work alternative technologies of water treatment or provide the water bypassing the Water Treatment Plant (e.g. water delivered by cisterns and water carts). Water treatment, water provided from reserve intakes in the necessary amount, should be made in the technological systems designed to remove water contaminants in water treatment plants, mobile water treatment plants and special filters. Minimum water pressure in the water supply network should be 0.1 MPa for the municipal water pipeline, 0.06 MPa for the rural water pipeline. If the CWSS does not work and in the areas not covered by the water supply network, water is provided from emergency wells.

Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption and the Water Framework Directive committed EU states to monitoring the drinking water quality. The EU Member States should take all means necessary to ensure regular monitoring of water quality in order to check if the available water meets the requirements of the current international legal regulations. It is estimated that the most effective in the implementation of the directive is the Drinking Water Inspectorate which manages drinking water quality in England and Wales. This organization supervises the companies producing drinking water and performs water evaluation.

It is now considered a risk assessment as a basis for taking effective preventive measures in order to increase the level of water consumers protection [8], [9]. Especially accepts the need to minimize the likelihood of danger to the life or health of water users [14], [16].

The subject of the paper is to develop the methods for failure risk analysing the CWSS functioning in crisis situations regarding its safety and reliability. The undertaken issues concern the methods of the analysis and assessment of risk associated with the CWSS operation in crisis situations (risk adopted as a measure of system safety).

2. Methods of risk analysis and assessment

Risk analysis and assessment can be defined as socio-economic decision-making process [1]. The rule is that you cannot eliminate the risk. You can only take different actions aiming at risk minimization to an acceptable level in terms of safety and necessary costs, which is said in the ALARP principle (As Low As Reasonably Practicable). Making the risk assessments we should answer to the fundamental questions:

- "What wrong may happen?"
- "How often?"
- "What would be the consequences ?".

Risk assessment is a comparison of the determined values with the risk acceptability criteria, which is the basis for the safety analysis. At this stage it is essential to determine the criteria for the risk acceptability, so that they can be used in decision-making process regarding the use of the system (e.g. repairs or modernization) [4], [10]. Such criteria should take into account the requirements linked to the subsystem reliability (in terms of both quantity and quality, in accordance with the valid legal norms and social and economic conditions).

Threats to the CWSS can be classified according to the type of cause [18]:

- internal (resulting directly from the operation of the system, such as damage to its components, failure in main or distribution pipes and fittings, pumping station failure),
- external (e.g. incidental pollution of water source, forces of nature, such as floods, drought, rain, storms, landslides, and the lack of power supply or actions of third parties - vandalism, terrorist attack, cyber-terrorist attack).

Generally, risk analysis methods are divided into [11], [12]:

- 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 [6] and event tree analysis, Bayesian networks, fuzzy logic and neural networks,
- simulation methods (e.g. Monte Carlo method) [26].

From the producer point of view, simulation methods involving studies in which the real system is described using mathematical models implemented on a computer, are important. The most important simulation methods that can be used in the analysis of water supply system functioning are: computer simulation methods that use well-known theoretical models, such as the Cross-Łobaczew method, the Ilian method, the Siertkin method, the Jaresko method.

The most popular programs used in Poland for the calculation and analysis of water supply network are: EPANET2 (USEPA), PICCOLO (Savage), WaterCAD (Bentley Systems), WODA (Computer Services T. Nidelińska Gliwice), InfoWater H2ONET/H2OMAP (MHW Soft USA).

The concept of water safety concerns primary the consumer. The secondary subject is the supplier – the manufacturer of water. In this regard, the risk can be considered as the consumer's risk and the manufacturer's risk [5], [20]. The important elements in this area are also the environmental aspect and the principles of sustainable development in the widely understood water management.

The risk analysis for the CWSS safe operation should be conducted in the following stages of reconnaissance:

- the determination of the number of people using the CWSS,
- the appointment of the representative failure events and analysis of their crisis scenarios in order to estimate losses,
- the determination of the probability (frequency) of undesirable events,
- the determination of the degree of water consumers susceptibility to undesirable events, analysis of the CWSS security system, including system monitoring and remote control, and the so called protective barriers included in the CWSS, such as alternative water supplies or multi-barrier components [15],
- the estimation of potential losses, including the probability of exceeding a certain value of limit losses,
- the determination of the risk level criterion according to the adopted scale (the three-stage risk scale: risk can be tolerated, controlled, unacceptable or the five-stage scale: risk can be neglected, tolerated, controlled, intolerable, unacceptable),
- the expressing the required risk reduction by means of the safety integrity levels (SIL) [7].

The limitation of the consequences of failure for the CWSS means [19]:

- the development of response plans in a crisis situation, including the possibility to supply drinking water from alternative sources,
- the development of alternative water treatment technologies in the context of the possibility of incidental events,
- the development of an information system and preventive actions,
- the current control of subsystem by performing systematic inspection, pipe renovation and modernization of the whole subsystem,
- the increasing of reserve margins (alternative sources of water, emergency volume in network tanks).

One of the most commonly used ways of risk analysis is the study of threats using the data from:

- the previous safety analyses,
- the conclusions from the occurred undesirable events and their causes,
- the experience of experts on the operation of existing water supply systems.

According to the directive of the European Union [24], the process of health risk assessment has the following stages:

- threat identification and assessment, based on:
  - physicochemical properties (physical state, boiling and melting points, density, vapour pressure, solubility in water and organic solvents),
  - the routes of absorption (inhalation, dermal, oral),
  - the type of exposure (sporadic, continuous, intermittent),
  - biotransformation (the level of toxicity of the substance resulting from the changes).
- the identification of consequences for health that may result from exposure to a specific substance,
- the evaluation of dose-response relationship to determine the correlation between a dose or concentration of a toxic substance and the frequency or severity of the occurrence of the biological effect of this substance in the exposed population [20], [21].

The evaluation of dose-response relationship allows to describe the quantitative relationship between the degree of exposure to a chemical substance and the size of toxic injuries or the frequency of occurrence and type of diseases caused by exposure to the substance. These data are derived from the results of experiments conducted on animals, less often on the basis of the results of studies concerning the exposed people.

Risk assessment process adopted by the WHO is based on the procedures developed for:

- chemicals which have a threshold mechanism of toxicity,
- substances which do not have a threshold mechanism of toxicity.

The aim of the identification of threats to which the water consumers are exposed is to show the type of substance found in drinking water, while the assessment of the risk level should be based on the identification of adverse effects of this substance on human health and its classification on the basis of all the available data. The influence of different substances on human health is determined by the appropriate specialists (doctors, chemists, biochemists, microbiologists), based on the results of laboratory and clinical studies and many years of experience.

The basis for the classification of hazardous substances that may be found in drinking water should be, first of all: the current regulation of Minister of Health on the quality of water intended for human consumption, the WHO guidelines, the EU regulations, knowledge and experience of the experts.

To threat identification, the results of epidemiological studies and the experiments made on animals, as well as the information about the similarity with the substance having proven harmful effects, are used.

Particular importance is given to the identification of carcinogens. The national classification of the carcinogenic substances is given in the Regulation of the Minister of Health of 2 September 2003 (Act of Laws No. 171, item. 1666), according to which the carcinogenic substances are divided into:

- substances with a proven carcinogenic effect, classified as category 1,
- substances that are considered to be carcinogenic, classified as category 2,
- substances with possible carcinogenic effect, classified as category 3.

Table 1. Safety integrity levels for Low Demand Mode and for High Demand/Continuous Mode

SIL	Low Demand Mode Probability of failure to perform its safety functions on demand	High Demand / Continuous Mode Probability of failure per hour
4	$10^{-5} \le PFD < 10^{-4}$	$10^{-9} \le PFH < 10^{-8}$
3	$10^{-4} \le PFD < 10^{-3}$	$10^{-8} \le PFH < 10^{-7}$
2	$10^{-3} \le PFD < 10^{-2}$	$10^{-7} \le PFH < 10^{-6}$
1	$10^{-2} \le PFD < 10^{-1}$	$10^{-6} \le PFH < 10^{-5}$

The measure of the system reliability is the concept of the safety integrity level (SIL) [7]. According to the standard, each requirement concerning specific risk reduction corresponds to the safety integrity level appropriate to the scale of risk reduction [2], *Table 1.* Calibration of risk graphs parameters [3]. *Table 1* shows how SILs are assigned to the probabilities of unsafe failures in the standard, one for low demand mode and one for systems with high demand or continuous mode.

3. Methods of failure risk analysis and assessment in the collective water supply systems in crisis situations

3.1. The risk assessment using risk graphs

3.1.1. The principle of the method

The simplest definition of risk (r) indicates that it is the product of the frequency of the probability of an undesirable event F and the size of possible damage associated with it C [14].

$$r = F \cdot C. \tag{1}$$

A more advanced definition of risk is three parametric risk estimation matrix determined by the formula:

$$r = F \cdot C \cdot E. \tag{2}$$

E corresponds to the size of the risk exposure.
For each threat four characteristics are determined:
- the frequency – F [1/year],
- the frequency of exposure – E [% year],
- the possible consequences – C [EUR],
- the risk – r.

The expanded risk assessment method takes into account the degree of protection that is inversely proportional to the size of the risk according to the formula [13]:

$$r = \frac{F \cdot C \cdot E}{O}, \tag{3}$$

where:
O – a degree of protection.
Risk valuation means the choice of the right ,,path", according to the earlier analysis of risk factors.

3.2 Risk graph

Classification of risk factors graph is presented in *Table 1* according to [7].

Risk parameters		Qualitative classification	Quantitative classification	Point scale
The frequency of threat occurrence - F	F_1	Incredible	< 1 in 30 years	1
	F_2	Unlikely	1 in > 3 to 30 years	2
	F_3	Sporadic	1 in > 0.3 to 3 years	3
The duration of exposure to risk - E	E_1	Negligible to average	< 10% of time	1
	E_2	Frequent to permanent	≥ 10% of time	2
The size of the possible consequences - C	C_1	Noticeable organoleptic changes in water, a nuisance that is not a health hazard, few consumer complaints	Less than 0.01	1
	C_2	Water quality standards slightly exceeded, consumers health problems, consumer complaints about water quality (e.g. unpleasant odour)	0.01 to 0.1 probable fatalities per event	2
	C_3	Hospitalization of exposed people is required, information in public media	> 0.1 to 1.0 probable fatalities per event	3
	C_4	Threat for consumers health or lives, serious toxic effects in indicator organisms, mass hospitalization, fatal cases, headlines in the media	> 1 probable fatalities per event	4
A degree of protection - O	O_1	A routine periodic monitoring of water quality	≤ 90% probability of avoiding hazard	1
	O_2	A routine periodic monitoring of water quality and on-line monitoring of selected indicators	> 90% probability of avoiding hazard	2

The way along the branches of the risk graph should begin by identifying the initiating/peak event being an undesirable event (e.g. secondary water contamination in the water network), then the level of potential consequences, the duration of exposure to threat, the probability of an event and a degree of protection should be defined [17]. For every situation a score is assigned to the parameters F, C, E and O, in this way we obtain a point scale to measure risk.

The values of particular risks (r) are determined using an appropriate formula (3). *Figure 1* shows the standard graph for risk assessment, and *Figure 2* the expanded graph. The risk valuation means the choice of the right "path".

The higher the threat and its consequences the higher safety integrity level SIL should be made.

Quantitative gradation of risk categories for the graph shown in *Figure 1* and *2* is presented in *Table 2*.

Table 2. Quantitative gradation of risk categories

Risk category	Quantitative gradation of risk	SIL
Inadmissible	16÷24	4
Unacceptable	8÷12	3
Controlled	3÷6	2
Tolerable	2	1
Negligible, no safety requirements	0,5÷1,5	---

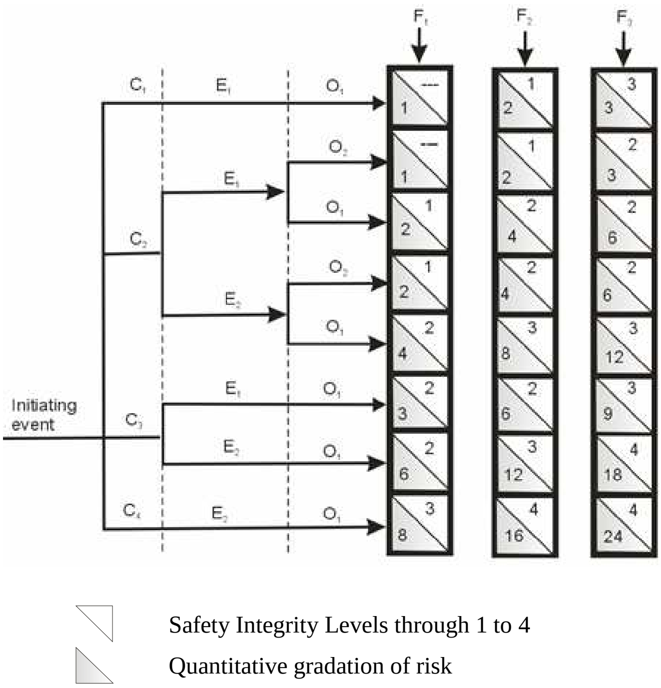

Figure 1. The standard risk graph

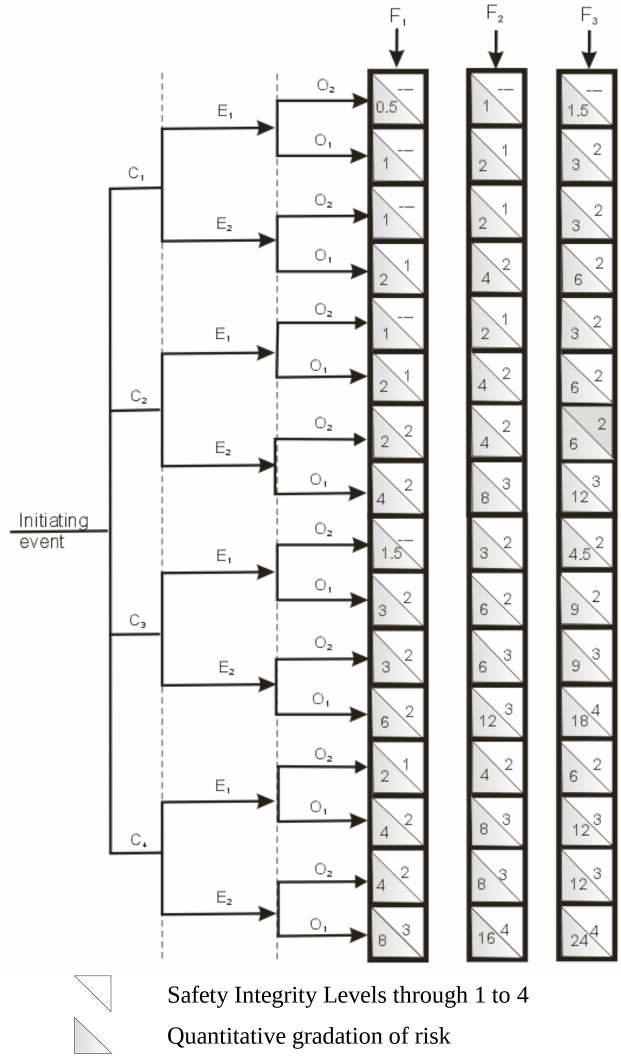

Figure 2. The expanded risk graph

The expanded risk graph, as opposed to the standard (commonly used), takes into account all the combinations for the possibilities of all risk factors.

If the tolerable risk is obtained, threats monitoring is required in order to maintain risk in this category. If the controlled risk is obtained, the risk should be lowered to the acceptable values. It is particularly important when point values are within the range of tolerable risk. The relevant actions involve costs that should be proportional to the obtained benefits. If the unacceptable risk is obtained, it is necessary to take action to reduce risk. When the emergency scenario associated with the unacceptable risk appears, shutting down of CWSS should take place.

2.2. An example of application of the method

The population of the city is supplied with drinking water from a central water supply system, whose source is flowing surface water. Monitoring of water quality includes the early warning system (raw water), the delayed warning system (treated water) and the late warning system (water in the network). Exposure of water users to possible threat is continuous. The risk of secondary chemical and microbiological contamination of water in distribution subsystem should be specified.

The following elements of risk graph were estimated:

- the size of the possible consequences – C_2
- the duration of the risk exposure – E_2,
- the frequency of threat occurrence – F_3,
- a degree of protection – O_2 .

The following path of risk graph was obtained, according to *Figure 2*, which corresponds to controlled risk assessment.

The following remedial measures should be taken:

- increasing the frequency of the water supply monitoring,
- improvement of the stability of the treated water,
- eventually predict the process of ozonation and filtration through granular activated carbon.

3. Conclusion

The development of appropriate risk assessment methods for CWSS in crisis situations contributes to reducing potential consequences of the failure, helps in making by the engineers, the designers and the government officials the appropriate decisions on the choice of the optimal solution, as well as methods of protecting CWSS users and the surrounding environment against the negative consequences. The analysis of the risk associated with the operation of CWSS should now be one of the priority activities undertaken by the water companies.

The method of the risk graph can be used to asses risk of drinking water consumers. The presented method is general in nature and focuses on the idea of methodological rules. For its practical application it is possible to develop individual segments to the required level of detail. The requirements in this regard will be determined by the specificity of the analysed CWSS.

Risk analyses should not emphasize the accuracy of the results but, first of all, the "success" or "failure" of projects related to the improvement of safety as a result of these analyses. The purpose of risk analysis is to provide the necessary information to make decisions on risk reduction.

The issue of risk reduction requires further studies and in this work it was only signaled.

Risks associated with the operation of the water supply system cannot be eliminated because it has the multi-causal nature. It can be, however, reduced to a tolerable level. Strategic aspect in this regard could be monitoring and auditing of CWSS. The presented expanded risk graph should be used for developed CWSS in large urban areas, it contains all the possible combinations of events. It enables to specify the category of risk for a given undesirable event in clear and fast way.

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References

[1] Aven, T. (2010). Conceptual framework for risk assessment and risk management. *Summer Safety &Reliability Seminars. Journal of Polish Safety and Reliability Association* 1, 15-27.

[2] Barnert, T. (2011). Determining required safety integrity level. *Summer Safety & Reliability Seminars. Journal of Polish Safety and Reliability Association* 1, 35-44.

[3] Heinz, P.B. (2012). *Safety integrity levels – Aprroach, methods, examples*. Educational Course: 6th Summer Safety & Reliability Seminars, Gdańsk-Sopot, 02.09.-07.09.2012.

[4] Hipel, K. W., Kilgour, D.M., Zhao, N.Z. (2003). Risk analysis of the Walkerton drinking water crisis. *Canadian Water Resources Journal* 3, 395-397.

[5] Hrudey, S.E. & Hrudey, E.J. (2004). *Safe drinking water.* Lessons from recent outbreaks in affluent nations. IWA Publishing, New York.

[6] International Electrotechnical Commission (2006) IEC 61025, Ed. 2.0, Fault Tree Analysis (FTA).

[7] International Electrotechnical Comission (2010). IEC 61508 – Functional safety of electrical/electronic/programmable electronic safety related systems, Geneva, first version issued 1999.

[8] Mays, L.W. (2005). *The role of risk analysis in water resources engineering*. Department of Civil and Environmental Engineering. Arizona State University, Arizona 2005

[9] Merkel, W. & Castell-Exner, C. (2010). Managing risk under normal operation and in crisis situations. *Water Utility Management International* 9, 19-22.

[10] Michaud, D. & Apostolakis, G.E. (2006). Methodology for ranking elements of water-supply networks. *Journal of Infrastructure Systems* 12(4), 230-242.

[11] PN-EN-1050. Zasady oceny ryzyka, 1999.

[12] PN-IEC 60300-3-9. Analiza ryzyka w systemach technicznych, 1999.

[13] Rak, J. (2005). Ocena bezpieczeństwa funkcjonowania SZW metodą grafów ryzyka. Komitet Inżynierii Środowiska Pan, Konferencja: XII Ogólnopolska Konferencja N-T z cyklu "Problemy gospodarki wodno-ściekowej w regionach rolniczo-przemysłowych" Komitet inżynierii Środowiska PAN. Białowieża 06-07.06.2005, t. 30, 237-246

[14] Rak, J. (2005). *Podstawy bezpieczeństwa systemów zaopatrzenia w wodę*. Wydawnictwo PAN - Komitet Inżynierii Środowiska t. 28.

[15] Rak, J. (2009). Selected problems of water supply safety. *Environmental Protection Engineering* 35, 29-35.

[16] Rak, J. & Pietrucha, K. (2008). Some factors of crisis management in water supply system. *Environment Protection Engineering* 34(2), 57-65.

[17] Rak, J. & Tchórzewska-Cieślak, B. (2006) Rozwinięcie metod oceny ryzyka SZW za pomocą grafów. Wydawnictwo Politechniki Krakowskiej. *Czasopismo Techniczne, Seria: Środowisko* 2, 179-188.

[18] Tchórzewska-Cieślak, B. (2010). Failure risk analysis in the water distribution system. *Summer Safety & Reliability Seminars. Journal of Polish Safety and Reliability Association* 1, 247-255.

[19] Tchórzewska-Cieślak, B. (2011). *Metody analizy i oceny ryzyka awarii podsystemu dystrybucji wody.* Oficyna Wydawnicza Politechniki Rzeszowskiej. Rzeszów.

[20] Tchórzewska-Cieślak, B. (2009). Water supply system reliability management. *Environmental Protection Engineering* 35, 29-35.

[21] United States Environmental Protection Agency (U.S. EPA.). Decision-Support tools for

predicting the performance of water distribution and wastewater collection systems. Washington D.C.: National Risk Management Research Laboratory Office of Research and Development U.S. Environmental Protection Agency. 2006.
[22] Water Framework Directive 2000/60/WE.
[23] WHO (2002). Water Safety Plans (Revised Draft), Report publication WHO/SDE/WSH/02.09 (World Health Organization, Geneva.
[24] WHO (2003). Guidelines for Drinking Water Quality, 3rd edn (draft) (World Health Organization, Geneva).
[25] World Health Organization, Water Safety Plans. Managing drinking-water quality from catchment to consumer, Water, Sanitation and Health. Protection and the Human Environment World Health Organization, Geneva, 2005.
[26] Zio, E. (2009). *Computational Methods for Reliability and Risk Analysis*. World Scientific Publishing Co., London.