Hazard identification and risk analysis of water supply systems

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Abstract: The risk analysis represents a modern approach of determining the level of provision of drinking water supplies for the consumers and the safety of the whole drinking water supply system. The authors of this paper present a methodology of risk analysis of drinking water supply systems and they deal with identification of qualitative as well as quantitative risks posted by the individual system components, the evaluation methods and interpretation of results. Problems relating to uncertainty and poor input data are solved by the application of an FMEA/FMECA technique, which is also demonstrated here on a case study concerning a water-supply tank. Some basic facts and first outputs of the national research project "WaterRisk" are presented in the last part of the document.

Introduction

The safety of drinking water depends on a number of factors, including quality of source water, effectiveness of treatment and integrity of the water distribution system that transports water to costumers. The current practice of designing and operating the water systems very often employs methods of mathematical modeling. However, the risk theory is applied for development and use of the models only seldom.

In May 2006, the European Commission and World Health Organization (WHO) launched a common project which aims at assessing the current experience with introducing risk analysis and risk management (RA-RM) principles in the process of drinking water production and distribution (Kožíšek, 2007). The RA-RM based approach will be implemented in the new issue of the Drinking Water Directive (DWD) during the coming years and water utilities will be forced to adopt it. A comprehensive RA-RM based methodology for implementation of these principles in the water industry is being developed in concordance with this trend in the national research project "Identification, quantification and management of risks of public water-supply systems – WaterRisk" in the Czech Republic. Brno University of Technology (BUT) is the leading research partner; National Institute of Public Health and a local water utility are the cooperating partners of the project. BUT is also a research partner of the EU project COST Action C19 that is focused especially on the hazards and risks of urban water infrastructures.

The risk analysis of water supply systems (WSS) has only been used for a relatively short period abroad and in the Czech Republic it is at its very beginning, using experience, methods and findings from other branches of industry. Due to extreme floods affecting Central Europe in 1997 and 2002, greater attention started being paid to the safety of drinking water supplies in the Czech Republic during these crises. Another major impulse implementing the risk analysis for the design, construction, and operation of WSS are failures of the individual elements and, above all, endangering and interventions in the system from the outside. In particular, after the events of 11th September 2001 in the USA, issues related to estimating, assessing and managing risks associated with drinking water supplies to the inhabitants have started being formulated and addressed mainly in large municipal agglomerations and extensive WSS.

It is important to divide the risks into quantitative and qualitative. Quantitative risks in the process of drinking water supplying are mainly represented by a lack, i.e. water supply interruption. Qualitative risks are mainly represented by poor drinking water quality, the determination of which requires implementation of a risk analysis method into the drinking water production, which will keep the water quality under permanent control.

Methodology for risk analysis of water supply systems

Terminology of risk analysis and general theory

At the very beginning of the WaterRisk project, a uniform terminology defining the exact meaning of some special terms was established. Some of the most important are as follows:

Undesired event (UE) – is a state when an element (system, part, product) loses its required property or ability to fulfil the required function in specific conditions. Undesired event is followed by undesired consequences.

Hazard – is a potential source (reason) of the undesired event.

Risk (R) – there exists no common definition of risk, but, for instance, IEC 300-3-9 defines the risk as a "combination of the frequency, or probability, of occurrence and the consequence of an undesired event". For the purposes of the WSS risk analysis, we have accepted and developed this definition of risk and have expressed it as follows:

$$R=P \times C \qquad (1)$$

where *R* stands for the risk, *P* stands for probability of occurrence of undesired event and *C* stands for consequences of the event.

Risk analysis (RA) – is a systematic application of available information about the hazard identification and estimation of risk which individuals, society, assets and the environment are exposed to. The risk analysis comprises the task definition and definition of validity extension, hazard identification, and risk estimation. It is a structured process that analyses both of probability and magnitude of consequences generated by specific activity, facility or system (IEC 300-3-9).

The risk analysis is a structured process identifying both the probability of occurrence of an undesired event, and the extent of adverse consequences arising from the event and it tries to answer the following three principal questions:

What can go wrong?	(Undesired events and hazard identification)
How likely is it?	(Frequency analysis)
What are the consequences?	(Consequence analysis)

Risk identification and risk estimation are not very common in the WSS sector. One of the reasons is the traditionally low risk of a failure of the system treating and supplying water. However, there has been recently a general pressure exercised by the industry on cost reduction while keeping or improving the reliability, safety or efficiency of the operated system.

One of the technical disciplines which may help achieve this target is the risk management. Generally, risk management is defined (IEC) as a "systematic application of management policies, procedures and practices to the tasks of analysing, evaluating and controlling risk", see. Fig.1 where we demonstrate the relationships between risk analysis, risk evaluation, risk assessment, risk reduction/control and risk management according to the definitions used in IEC 300-3-9.

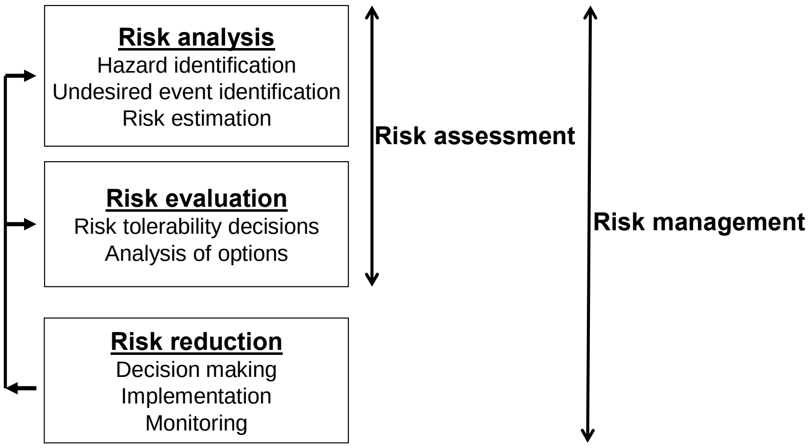

Figure 1.1 Risk assessment and management

Risk analysis under uncertainty

The major problem is always how to calculate or estimate the values of *C* and *P* under uncertainty - lack of data, insufficient historical records and/or unreliable data, uncertainty of failure detection, uncertainty of employed methodology of risk analysis and proper interpretation, etc. This problem may be effectively solved by using frequency instead of mathematical probability of occurrence of undesired event and also by employing the FMEA/FMECA methodology. FMEA uses categorization of probability of occurrence, severity of consequences and all other potential inputs into categories. For instance, categories of frequency of occurrence may be as follows: almost certain – likely – moderate – unlikely – rare. The category is then represented by its point-score only, e.g. almost certain 5, rare 1. Each analyzed element is to be assigned into one of the categories. This is done based on some chosen factors or indicators and, of course, based on limits of categories. Limits are set up by expert with sound knowledge of the system. This is a very efficient approach especially in the situation where hard data is missing and the analysis has to be based on "soft" data. A semi-qualitative model is constructed where experts' qualitative information is very effectively used together with quantitative (statistical or empirical) hard data.

The failure mode and effects analysis (FMEA) and Failure mode, effects and criticality analysis (FMECA) are reliability methods that enable assigning failures with significant consequences affecting functionality of the system. The general methodology of FMEA/FMECA is standardized by IEC 812. Both the methods are very suitable for risk analysis of technological system including WSS. Basically, the analysis begins with choosing the element from the lowest level for which enough information is available. At this level, several tables are created describing different failure modes that may occur on each element of the level. Elements are assessed particularly one by one and consequence of the failure of each of them is considered as a failure mode when consequences of the failure are analyzed at the next higher level. This way the analysis proceeds bottom-up-ward and the result is assignment of consequences of the failures with the specific failure modes at all required levels up through the whole system as a unit.

Risk structuring

The concept of risk structuring has been well known and has been presented at specialized conferences many times (e.g. Tuhovcak, Rucka, 2005). Principally, for the purpose of risk analysis the WSS is divided into four subsystems, overall consequences are considered as multidimensional vector, which is composed of its four basic parts, and also hazards are divided according to its origin into three basic categories. The overall structuring is shown in Figure 1.2.

WSS parts	Origin of hazard	Consequences
Water source	Natural hazards	Health
Water treatment	Manmade threads	Economic
Water distribution	Technical and technological hazards	Socio - economic
Service connections and plumbing		Environmental

Figure 1.2 Risk structuring

Generic framework of risk analysis of water supply systems – project WaterRisk

No matter what the complexity of the analysed WSS is, the generic framework of risk analysis still remains the same. The following scheme represents the basic principles of the analysis as it is also implemented in the developed software application, see Fig.1.3.

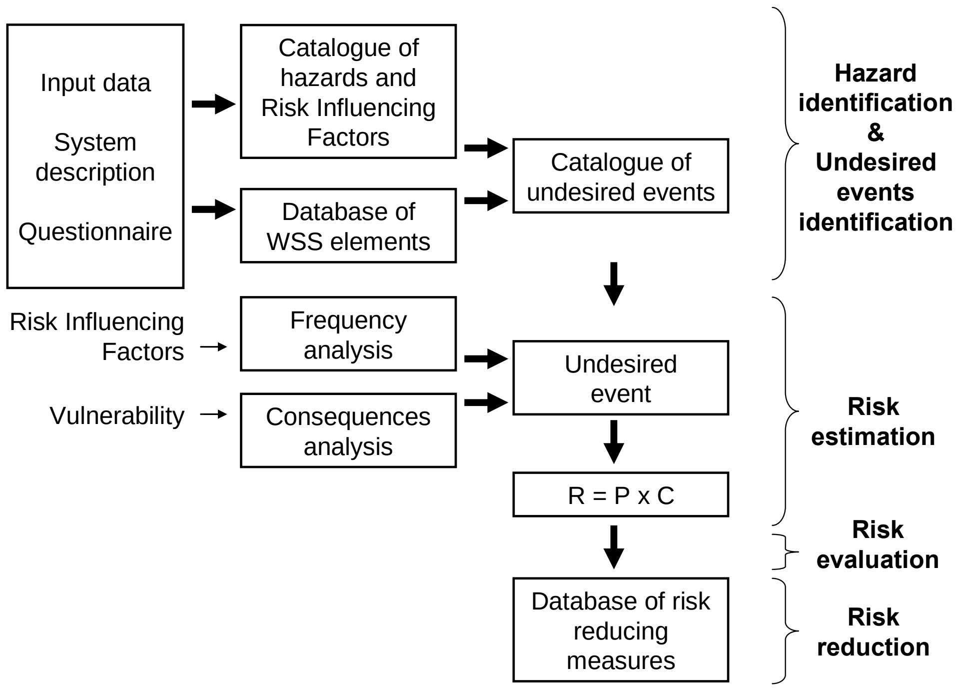

Figure 1.3 Generic framework of risk analysis of water supply systems – project WaterRisk

Water supply system description

The very first step is always decomposition, detailed description and technical audit of the analyzed WSS from the catchment area to the tap including water resources, treatment technologies etc. The enduser does it himself using the advantages of the database of WSS elements that contains all predefined theoretically possible elements of a conventional WSS, see Figure 1.4. The enduser is only supposed to pick those parts that are present in his WSS and describe their, from the risk analysis point of view, important properties like dimensions, age, functionality, operating conditions, known problems and so on.

The contemplation on the aim of the analysis should be done in this initial phase of analysis. It is important to clarify what will be analyzed (part x unit), what sort of WSS it is (simple x complex) and what level of detail will be distinguished (water tank = 1 unit x water tank = 15 particular parts). When the WSS is defined and described, the next step of analysis can be performed – the hazard identification.

Ref.	Water-supply tank
3.01.01	Accumulation chamber
3.01.02	Manipulation chamber
3.01.03	Ventilation
3.01.04	Intake
3.01.05	Emergency spillway
3.01.06	Withdrawal
3.01.07	Outlet
3.01.08	Sewerage
3.01.09	Fittings, valves
3.01.10	Pipes
3.01.11	Disinfection
3.01.12	Metering and monitoring
3.01.13	Operation and control
3.01.14	Security system
3.01.15	Backup energy source
3.01.16	Other

Ref.	Undesired event
01	Damage/destruction of the construction
02	Deterioration of water quality
03	Drinking water contamination
04	Formation of sediments on the bottom

Ref.	Undesired event
01	Damage/destruction of the construction

Figure 1.4 Example of defined undesired events for some elements of water-supply tank

Catalogue of hazards and risk influencing factors

The aim of this procedure is to compile a comprehensive list of all practically possible hazards that may occur in the WSS and generate undesired events. Hazards are identified by the enduser who takes advantage of the catalogue of hazards and risk influencing factors (RIF) which is a hundred-items-database serving as a checklist. Each hazard is followed by conditions of its relevance and comments on impending consequences. Each item in the list has also its numerical ID and attributes indicating parts of the WSS where the hazard is relevant, see Table 1.1.

Table 1.1 Catalogue of hazards and risk influencing factors – example from category of technical hazards

Ref.	Hazard	Potential undesired events	Conditions of relevance	Water source	Treatment	Distribution	Service connections
3.21	Operating pressure is too high	water delivery interruption, higher pipe bursts	> 0,60 MPa	0	0	1	1

The Enduser goes through the list one by one item and assesses the importance/relevance of each of them. Conditions of relevance serve as a requisite for inexperienced users. Risk is not estimated here. The only aim is to state which hazards are present in the WSS, which are not present and which are not assessed e.g. for lack of data (options of rating 1; -1; 0). One of the outputs from this technique is a score which is processed subsequently.

Catalogue of undesired events

It is a specific list of undesired events or failures of particular parts of the WSS with interaction to the formerly identified hazards and risk influencing factors that may cause them. UE is defined for a certain part of the system; there may be more then one UE for each part and each of them must be properly described (what, when, how - scenario). The content of the catalogue is generated ad-hoc by the software application according to the type of WSS, its parts and formerly identified hazards. The risk is analysed separately for each UE – consequences and frequency of occurrence is estimated by means of a tailored methodology. For instance, for a water-supply tank there has been appointed and described five particular undesired events so far, see Figure 1.4.

Table 1.2 Catalogue of undesired events for accumulation chamber of a water-supply tank

Type of hazard	Ref. / Element	Ref.	Hazard	Ref.	Undesired event	Potential consequences	Type of consequences				Type of risk	
							Health	Economical	Socio - economical	Environmental	Qualitative	Quantitative
NATURAL HAZARDS	3.01.01 / Accumulation chamber	1.01	Storm rainfall	01	Damage/destruction of the construction	reinforcement corrosion, mechanical damage of the construction, backfill scouring	0	1	1	0	0	1
		1.02	Acid precipitation	01	Damage/destruction of the construction	reinforcement corrosion, mechanical damage of the construction, chemical corrosion of the concrete	0	1	1	0	0	1
		1.03	Snow, hailstorm, ice, coating of ice	01	Damage/destruction of the construction	formation of microfissure network, decreasing of water impermeability of the tank, mechanical damage of the construction	0	1	1	0	0	1
		1.05	Windstorm	01	Damage/destruction of the construction	outer casing failure (water towers), sealing failure	0	1	1	0	0	1
		1.14	Earth quake, landslides, subsidence, setting	01	Damage/destruction of the construction	formation of microfissures, loss of stability, loss of water impermeability, sealing failure	0	1	1	0	0	1
		1.16	Groundwater - flow, creeping, phreatic fluctuation, corrosivity	01	Damage/destruction of the construction	formation of microfissures, loss of stability, loss of water impermeability, concrete corrosion, reinforcement corrosion	0	1	1	0	0	1
… the catalogue of undesired events continues by social, technical and technological hazards for all parts of the water-supply system												

Frequency analysis

Frequency analysis aims to estimate the probability of occurrence of each analyzed UE. A tailored methodology has been developed for each UE separately, see Table 1.3. Generally, water utilities fight against a lack of input data for qualitative analysis techniques. That's why the FMEA/FMECA semi-qualitative technique has been chosen and implemented for that procedure, because FMECA makes it possible to assign the analyzed UE according to the frequency to one of defined reference categories K1-low/no probability up to K3 – very high probability using a set of specified subsidiary indicators (e.g. technical indicators). Boundaries between the categories must be set up uniformly before the analysis by expert, see Table 1.4.

Table 1.3 Frequency analysis for undesired event 01 – Damage/destruction of the construction of accumulation chamber (part)

	Ref.	Hazard	Subsidiary indicators, criteria	Yes/No	Score
NATURAL HAZARDS	1.01	Storm rainfall	Concrete corrosion, reinforcement uncovering and/or corrosion	No	2
			Concrete constructions wetting	No	2
			Outer constructions uncovering - in case of high slopes	Yes	2
			Backfill washing	Yes	1
	1.02	Acid precipitation	Reinforcement corrosion	No	3
			Concrete chemical corosion - massive ruptures in the construction	Yes	2
			Dropping the concrete off the wall	No	2
	1.03	Snow, hailstorm, ice, coating of ice	Massive ruptures in the construction	No	3
			Ceiling plate rupture	No	3
			Concrete constructions wetting	Yes	2
			Formation of microfissure network due to freezing of moisture content in the concrete	Yes	2
			Minor damage of the outer casing (water towers)	No	1
… analysis continues by other natural, social and technical hazards				Maximal score:	25
				Total score:	9 = K2

Table 1.4 Boundaries of particular frequency categories

Category	Reference category - Reference category verbal description	Percentage boundaries (score)
K3	High probability	> 67%
K2	Medium probability	34 - 66%
K1	Low probability	< 33%

Consequence analysis

The aim of the consequence analysis is to estimate the severity of UE consequences. Consequences of all UEs in the whole WSS are analysed by means of a unified methodology that takes into account four basic categories of consequences. These are as follows:

Personal injuries and deaths,

Economic losses of water utility,

Socio-economic losses (e.g. amount of non-revenue water, presence of sensitive customer, duration of water delivery interruption, number of affected consumers, lack of fire-purpose water, inadequate pressure in the network, etc.),

Environmental damages.

For each of the four consequence categories there has been described certain dimensions that will be evaluated (e.g. duration of water-supply interruption). Although there are many options to express and structure risks, origin of hazards and consequences; the above described structuring has been used in the WaterRisk project with success.

Risk quantification and evaluation

After the frequency and consequences for each UE have been estimated, the quantification of risk for each UE is processed. For that purpose a standardized risk matrix is used, see Figure 1.5. Basically, three levels of risk are distinguished. These are as follows:

None or negligible risk – there are no risks to be reduced,

As low as reasonable possible risks (ALARP) – the risks in this area are dedicated to more detailed discussions; usually cost/benefit analysis is processed and trade-off values are quantified,

Intolerable risk – no doubt that risk reducing measures must be taken for the risk in this area.

Risk matrix		Consequences		
Frequency	Category	K1	K2	K3
	K1	None or negligible		
	K2		ALARP	
	K3		Intolerable	

Figure 1.5 Risk quantification and evaluation by risk matrix

Database of risk reducing measures

Those undesired events that generate highest risk are determined to take some risk reduction measure. The risk can be reduced by decreasing its components – probability and/or consequences. WaterRisk provides a database of risk reducing measures to the enduser that are defined specifically for each undesired event. The enduser can choose the best one for his case and reanalyse (simulate) the risk after the measure has been taken.

The risk analysis finds weak spots in the WSS and estimates potential risks. Subsequently, the risk reducing measures are designed on that basis. The final step is a compilation of a Water Safety Plan that utilizes the risk analysis results and follows up on its findings.

Conclusion

The theory of risk analysis and risk management has started being implemented in a wider spectrum of human activities in recent years. In the water industry it is being used for creating flood maps where areas are assessed according to the level of risk generated by floods at different frequency-rate. In the water-supply sector, the first idea of the HACCP principle implementation appeared in 1994 (Havelaar). Since the second half of the 1990's, it has been legally introduced in several states. Since 2000, many large utilities have applied the RA-RM principles voluntarily (similarly to ISO 9001 etc.). Since 2004, the system of risk analysis and risk management has been the so-called "Water Safety Plans" and has represented the WHO's official strategy when it became a part of the 3rd Guidelines for drinking-water quality. In the coming years it is envisaged that the RA-RM principles will be legally introduced and obligatorily used by water utilities in the process of drinking water abstraction, production and distribution in all EU countries.

Along with this European trend of increasing drinking water safety and quality goes also the Czech national research project WaterRisk that aims at developing a methodology for implementation of risk analysis and risk management principles in the public water supply systems in coordination with Working Area 4 of the research project TECHNEAU. In the near future, the catalogue of undesired events will be finalised, UEs with their risk influencing factors for all system components will be described, and a methodology for their frequency analysis will be developed. Also, a catalogue of hazards will be compiled. It is envisaged that the software application will be displayed on the public project website at **WaterRisk.cz** and will serve as a web-based interactive tool during 2008. At the last project phase, the methodology and software will be tested on several real case studies.

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