RISK ANALYSIS OF THE DRINKING WATER SUPPLY SYSTEM OF THE SMALL VILLAGE

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The article deals with the application of risk analysis methods to the problems of the drinking water supply by public water supply systems. The examples of a risk analysis and the prioritization of proposed corrective measures are demonstrated on the example of a small municipal water supply system. Within the project WaterRisk a detailed methodology for risk analysis of public water systems was developed, which was subsequently fully implemented in a WaterRisk.cz software tool. With the help of this software the risk analysis can be performed at large - complex water supply systems, as well as at the small ones - simple public water supply systems, for which the methodology is specially adapted. The result of a risk analysis is among other things also a list of remedial measures which have to be implemented in the water system in order to eliminate the identified risks. The tool was developed with a focus on prioritizing of these remedial measures, while maintaining a comprehensive approach and perspective. The practice shows that it is not possible for operators, respectively, owners of public water supply system, to eliminate all risks simultaneously. It is necessary to complete these steps gradually and split them for the longer time period. It is also necessary to take into account a wide range of external influences and circumstances that enter into the decision-making process. In the case of investment events it is usually about challenging economic projects, which play a decisive role. The decision support system based on risk analyses in this processes offers interesting possibilities of the use. Using a developed methodology is presented in the paper on a case study of a small public water system in the Czech Republic.

KEYWORDS
Drinking water, risk analysis, software, water supply system, case study

1 INTRODUCTION

In recent years methods of risk analysis and risk management have been applied in a wide range of fields of human activities, including the water supply sector. These are promising methods, which record a significant development and in the field of public drinking water supply provide the tools for ensuring safe drinking water, improving the water quality and services and enable the prioritization of investment measures with limited financial resources and the uncertainties in the initial information. This approach is also supported by the legislation. The quality of drinking water in public water supply systems in the Czech Republic is governed by the Decree no. 252/2004 Coll. of Ministry of Health in the Czech Republic. The operation of public water systems is regulated by the Law on Water Supply and Sewerage no. 274/2001 Coll. as amended and the related Decree 428/2001 Coll. as amended, which is carried out by this law. All three of the above mentioned regulations are based on and in accordance with EC Directive 98/83 / EC Drinking Water Directive (DWD), which is the main legislative document in the field of water supply sector in the EU countries. In terms of the application of the principles of risk analysis particularly its latest amendment Commission Directive (EU) 2015/1787 of October 2015 is essential, which imposes a duty on a responsible entity to continuous monitoring of the water quality during its production from the source to a tap of consumers. It is recommended that for this purpose the so-called Water Safety Plans (WSP) should be developed for public water supply systems, which are based precisely on the basis of the risk analysis [Davison 2005]. It is therefore possible to conclude that the technique of the risk analysis in the field of water supply sector is a well-established legitimate tool that can be used not only to control the quality of the drinking water in public water supply systems, but as a generally used tool for a decision support and solving complex problems, such as the decision on the reconstruction of the individual system components, their mode of operation, the construction of new buildings, etc.

In connection with the problem of ageing water infrastructure the owners of water supply systems solve very often a problem when the end of life of most of parts of the water supply system is gradually nearing at the same time and their overall reconstruction or an extensive repair is essential. Typically, these are difficult situations for investments when it is necessary to reconstruct e.g. the large parts of the old water mains, served out water tanks or dilapidated water treatment plants.

Figure 1. The illustrative example of a dilapidated water treatment plant. A settling tank (on the left) and the sand filtration

The unsatisfactory technical condition of the pipelines and constructions has a negative impact on the reliability of the water supply system and the quality of drinking water supply and generates considerable risks in water supply systems. We know from experience that many owners and operators of public water systems in the Czech Republic (CR) annually renew and reconstruct significantly less than 1% of the total length of operated water mains. In simplistic assumption that the average theoretical lifetime of these pipelines is about 80-100 years, it means that even a simple reproduction of the infrastructure is not assured. The problem is thus has been accumulated for a long time and postponed for the future. Meanwhile the construction of the water infrastructure in CR did not work evenly in the past. For example, from 1960 to 1970 it was built much more intensively [Tuhovcak 2016]. In view of the limited economic and human resources it is usually not realistically possible to implement the general reconstruction of all necessary elements of water supply systems simultaneously, and the owners are forced to choose which elements to reconstruct in priority in the short term and which of them to renew later. While making this decision a variety of factors comes into action such as, the age and the technical condition of the pipeline or the construction, the impact on the quality of the distributed water, the significance of the construction and its impact on the overall reliability of the water supply system, the quantity of supplied people, the coordination of overlapping of the reconstruction with other utility services, etc. This issue has been already relatively well processed also in literature. For the selection of priority measures one of the methods of multi-criteria selection is commonly used, where each measure, i.e. the project of the reconstruction of a particular element of the system, is evaluated by several defined indicators with a predetermined manner and the scale evaluation [Tuhovcak 2014]. The final evaluation is then carried out by different ways of aggregation of the results. One of the ways to determine the order of the measures is the application of the theory of risk analysis and management.

2 RISK ANALYSIS METHODOLOGY OF PUBLIC WATER SUPPLY SYSTEMS – THE WATERRISK PROJECT

This issue has been recently discussed in great details by the scientific research project entitled ***"Identification, quantification and management of Risks of public water-supply systems"*** no. 2B06039, which was presented to the public under the acronym "WaterRisk". Besides the detailed methodical process of the risk analysis of public water supply systems the software application WaterRisk.cz was also developed. This is the web database software, which through an Internet browser allows users to use the risk analysis to assess their drinking water supply systems. The development of this tool was running from 2006 to 2010 at the Institute of Municipal Water Management, Faculty of Civil Engineering Brno University of Technology. Since 2010 this tool has been utilized in practice and open to the professional public on www.WaterRisk.cz

With regard to the further understanding of the text, we consider it essential to explain the following terms, which are used by the created methodology.

Risk analysis (RA) is the systematic use of available information to identify any hazards and to estimate the risk for individuals or population, property or the environment. Risk analysis includes the definition of objectives of the analysis, the validity scope, the hazard identification and the risk estimation. It is a structured process that identifies both the likelihood and the extent of the undesired consequences derived from the activity, facility or system [ČSN IEC 300, 1996]. Risk analysis tries to answer three basic questions: (1) What could go wrong – the hazard identification; (2) How likely it could happen – the analysis of frequency; (3) What consequences there could be – the consequences analysis.

There has existed no universally and completely accepted definition for the term "**Risk**". Each of the branches that have implemented this theory also introduced its own terminology and a new or modified definition of the risk. For the purposes of this methodology the risk is expressed in accordance with ČSN IEC 300 as a combination of the frequency or probability of occurrence of a specified undesired event and its consequences. Thus the risk has always at least two components: the frequency or probability "P", which the undesired event occurs with, and the consequences of the undesired event "C". We express it by the symbolic relationship for the need of the risk quantification:

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

where R expresses the risk priority number and P is the probability of the realization of the undesired consequences C. In order to quantify the risk, it is necessary to evaluate both its parameters. If one of the two components does not exist, there is no risk.

The undesired event is an event when an object (a system, a component of the system, a product) loses its desired quality or ability to perform the required function – e.g. the drinking water is no longer safe or sensory acceptable for consumers (e.g. the presence of pathogenic micro-organisms or toxic or smelling substances) or the water system stops supplying water in the desired quantity or pressure. The undesired event is accompanied by creation of the undesired consequences and is always defined for a particular element of the system. The undesired event is in fact a malfunction of the water supply system.

Result, consequence (C) is an impact, eventually a damage caused by the realization of the undesired event. The consequences in the theory of the risk analysis are identified by the letter "C" and create one of the fundamental components of the risk. Overall consequences are set as a combination of sub-components of the consequences, which are determined separately and correspond to the individual categories of consequences. The created methodology defines four categories of the consequences as follows: (1) health consequences - effects on the health of consumers of drinking water; (2) economic consequences - damages caused to water companies; (3) socio-economic consequences – the perception of the quality of services from the perspective of consumers of water; (4) environmental consequences – the environmental impact. The so-defined structure of the consequences will ensure a comprehensive system of risk assessment, taking into account the impact on all parties concerned.

The advantage of the application of risk analysis to the problems of decision making and prioritization measures in water supply systems is to provide a comprehensive view. The scenarios of the kind "what happens if ..." are analyzed and their evaluation is done in terms of their probability of their occurrence and the threatening consequences. With regard to the scope of the article it is not possible to present the entire AR methodology, more detailed information, for example, is introduced in [Tuhovcak, 2010].

3 CASE STUDY - RISK ANALYSIS OF A SIMPLE MUNICIPAL WATER SUPPLY SYSTEM

The developed RA methodology for the public water supply systems (WSS) has been applied since its publication on several WSS, where its practical applicability and validity of the results were verified. The processing of the analyses is done completely in the WaterRisk.cz software application. One of the case studies where the risk analysis was used to fully assess the risks was a small village WSS in Hradek in the Czech Republic.

3.1 Public water supply systemn in Hradek

This is a simple small public WSS, which supplies 761 people with drinking water. A total number of 248 real estates' are connected to this water supply, 247 of which are houses or buildings of the public facilities with a maximum of two floors. In the centre there is a hotel and a wellness centre, which are located in the castle. The scheme of the water supply system is shown in Fig. 2.

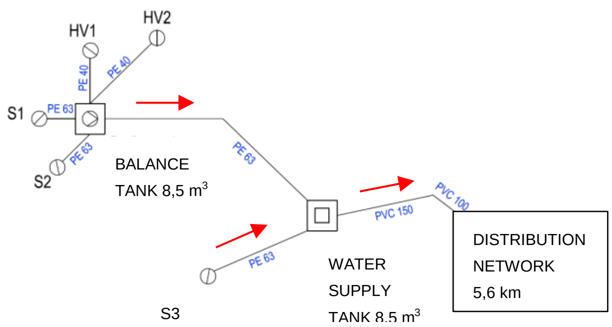

Figure 2. The scheme of the water supply system of the village Hradek

The water supply system has three separate spring areas in which there are 5 intake units S1, S2, HV1, HV2 and S3. The total capacity of all water resources is 2,0 $l \cdot s^{-1}$. The water is pumped from the source into a single water supply tank of the system, which has only one storage reservoir of 100 m^3. In the water tank sodium hypochlorite is dosed by a dosing pump directly into the storage tank. At the drainage to the consumption area the inductive flowmeter is located. The water supply system comprises a total of 8.3 km of a pipeline, of which the feeding line constitutes 2.1 kilometres, the supply lines from the water tank into the consumption area is 0.6 km and the distribution network in consumption areas is 5.6 kilometres long. The material composition of the pipeline network is as follows: polyethylene (PE) 40.3%, polyvinyl chloride (PVC) 35.6%, cast iron 20.8%, steel 3.2%. The average age of the network is 38 years. According to the hydraulic analysis the operating pressure is of nearly optimum range from 0.38 up to 0.55 MPa, the average value is 0.48 MPa [Brezina 2011].

Figure 3. Securing of the water resource (on the left), securing of the tank

Figure 4. The fitting chamber of the tank with flowmeter (on the left), dosing of the disinfection and an open entrance to the water level in storage reservoir

Before commencing the actual risk analysis it is essential to get to know the considered water system and to verify the manner of its operation. With regard to the quality of the results and the accuracy of the conclusions of the risk analysis it is also recommended to develop several partial technical analyses which will provide more detailed information about the considered system. This is e.g. the processing of the information from the service daybook, the analysis of the water consumption and water losses, assessing the technical condition of the constructions, pipes and fittings, the analysis of a malfunction, the hydraulic analysis of the water supply network, analyses of the quality of raw and drinking water, etc. This information will significantly improve the following decision-making processes and their knowledge reduces the uncertainty of the results of the risk analysis. However it is not a necessary condition, the risk analysis can be processed without these analyses, but the uncertainty of the results obtained will increase. A crucial role is played by the communication with the operational techniques of the water supply system.

Detected failures of the water supply system

According to the information gathered by us among the most common defects and operational issues of the considered water main there belong:

- The failures of the pumping in the water resources - there are frequent electrical faults, level recording and fastening of the pumps, and also pumps' motor disorder. The cause is the relatively high age of the pumps (in average 15 years), the condensing of humidity and leaking of the rainwater into the electrical switchboards during heavy rains. The frequency of the failures is 7 times for the last 15 years. These defects are not detected automatically – there is no system for the operational monitoring. As a result the pumping failure will lead in a few hours to empty out the tank and subsequently to the interruption of the drinking water supply.
- The water quality in the spring S3 varies depending on the amount of the rainfall. During torrential rains and the spring snow melting the turbidity of raw water occurs in a source. Consequently, the whole tank must then be depleted and the spring must be temporarily put out of the operation. It cannot be put out of the operation permanently; there is not an adequate reserve capacity of water resources. The automatic monitoring of the water quality in the source is not set up. The operator puts the spring out of the operation preventively according to the experience.
- The water tank has an insufficient storage capacity of 1x 100 m^3. Optimally, it should have two storage reservoirs, each with a capacity of 100 m^3. The operation of the water tank with a single storage reservoir generates significant operational problems while the cleaning when it is necessary to interrupt the operation of the WSS. The fitting chamber is in a desolate state; consequently, handling the valves is very difficult. The construction object of the reservoir is in an unsatisfactory technical condition – the rainwater leaks into the storage tank through the cracks in the ceiling, which generates a significant risk of microbial contamination of water and a deterioration of its quality.
- The high failure rate of the pipeline - the average failure rate of the pipeline for the last 5 years has been 0.85 km failure$\cdot km^{-1} \cdot year^{-1}$, which is a relatively high value. On the water network there occur in average 7 failures per year. It is worth noting that the majority of failures occur on the series supply of PVC from 1973 immediately below the reservoir. This number includes only the detected failures which have been detected due to a massive water leak and had to be repaired immediately. Small hidden leaks on the network that cannot be traced make an overall flow of 0,21 $l \cdot s^{-1}$. The ILI indicator of the overall system for the year 2015 is 2.1.

Figure. 5 Repairing of pipelines' failure - cast iron pipe DN100 from 1965, encrustations of the internal surfaces

From the above given description it is evident that the water supply system in Hradek exhibits a relatively high number of operating defects caused by the inadequate technical condition of the individual system elements: non-capacitive sources (the colmatage of the drill wells, high ageing and the failure of the pumping equipment), a leaking and non-capacitive tank, the increased failure of some water mains. In terms of the limited financial resources, it is not realistically possible to reconstruct all the necessary parts of the WSS at once. Therefore, the risk analysis was carried out, which defines the level of risk that generates the undesired individual conditions (i.e. failures) that can occur in the system. The order in which various measures on the water network will be implemented is determined according to the level of risk, and they generate individual elements of the system, respectively, the undesirable events which occur in these elements. The measures will be implemented in such a way as to eliminate the highest risks in priority.

3.2 The process of the risk analysis

The risk analysis in the WaterRisk.cz software application is fully automated and consists of the following steps:

- The description of the system - using a catalogue of standardized elements of WSS all elements of the considered system are defined and provided with a description and their characteristic parameters.
- The hazard identification - using a standardized catalogue the hazards are identified that can occur in the considered WSS, respectively, its individual parts. In the case of this WSS there were identified 13 hazards out of the total possible 59 in the part of water resources, as well as 13 hazards out of the total possible 66 in the distributional part of the water supply system, and 0 hazards out of possible 52 in the part of the treatment of water (because there is no water treatment plant in the system). As an example, there is a list of real hazards in the water resources part: (1) Natural hazards - 1.03 Snow, hail, ice, frost; 1.04 Lightning, electric shock; 1.06 Drought; 1.08 Flood, special flood; 9.1 Global climate change; 1.18 Radioactivity, radon; (2) Social hazards - 2.18 Agricultural pollution; 2.22 Old environmental burdens; (3) Technical and technological hazards - 3.01 Failure of the electricity supply; 3.03 Failure of the device; 3.18 Stray currents, corrosion; 3.19 Ageing of a material and changes of its properties; 3.21 Poor technical condition of the construction, pipes and fittings. Each of these hazards is provided by a qualifying description in the catalogue.
- Generating of the undesired events - based on the existence of various individual types of elements in the considered WSS and real hazards, the software application will automatically generate from a redefined list of all theoretically possible undesired events for further evaluation only those undesired events that may occur realistically in the considered system. In this system 47 undesired events have been generated for further evaluation, including 25 of them for the part of the water resources and 22 for the distributional part of the water supply system.
- Risk Analysis – a user evaluates the likelihood of occurring of the undesired event for each of the generated events according to the predefined criteria, and the possible consequences. The result of this evaluation is the value of the risk priority number R, which every undesired event is evaluated by.

The overview of undesired events in the whole considered WSS and their evaluation shows the risk matrix in the application, see Fig. 6.

Rating		Consequences		
		C1	C2	C3
Probability	P1	6/0/11 K1 - negligible	8/0/0 K2 - low	0/0/1 K3 - moderate
	P2	6/0/2 K2 - low	0/0/2 K3 - moderate	0/0/3 K4 - high
	P3	0/0/1 K3 - moderate	5/0/0 K4 - high	0/0/2 K5 - very high

Figure 6. WaterRisk.cz application - risk matrix of the public water supply system in Hradek

As apparent from Fig. 6, there are two undesired events that generate the highest risks in the category K5 - very high. Both are in the distributional part of the WSS (the third number after the slash). In the water resources part (the first number after the slash) or in the water treatment part (the second number after the slash) there are imminent undesired events in this category. The highest level of risk is generated by the undesired events "307 Violation / destruction of building structures of the water tank handling chamber" and "301 Violation / destruction of building structures of the storage reservoir ". Because of the very bad technical condition of the reservoir both states were rated with a high degree of probability of P3 occurrence. While implementing this undesired event high economic costs would arise and the supply of drinking water would be immediately interrupted, so they were both assessed by very high C3 consequences. In a similar manner the remaining 45 undesired events were also assessed, with respect to the scope of the contribution, however, they will not be listed in detail. Evidently the water supply tank is threatened by the highest risk in the entire WSS, which should have a priority in the draft of measures.

3.3 The proposal of measures for the risk mitigation

In the next step for each undesired event in the risk matrix the corrective measure is defined that will mitigate the risk. It is exercised in the direction from the highest to the lowest risk. The risk mitigation, which generates the selected undesired event of the system, is achieved by reducing the likelihood of its occurrence and/or reducing the extent of its potential consequences. Remedial measures can be of the investment measures type (reconstruction, repairing, replacement of the equipment, a construction of a new structure, etc.), or it may be an organizational measure. It can be e.g. the introduction of monitoring, change of the way of the operation, increasing of the frequency of inspections of the given element, etc. It is usual that the implementation of one measure will mitigate the risk for several undesired events simultaneously.

For example, in the case of the considered WSS in Hradek a prior attention was given to the constructions of the water supply tank, which generates the highest risk in the system. It was decided to build a new water supply tank with a volume of 2x 100 m^3, which will replace the dilapidated and technically inadequate existing water tank. The amount of investment has been tentatively estimated at 0.11 million EUR (2.8 mill. CZK). By this measure a mitigation of the accumulated value of risk priority number (sum of particular risk priority numbers of all the undesired events in the WSS) will be achieved for the whole WSS from the original value of 110 (point A in the graph of Fig. 7) to the value 89 (point B). Specifically the following will be achieved:

(1) The minimizing of the likelihood of undesired events occurrence of no. 307 and 301, and at the same time

(2) The mitigation of the likelihood of worsening of the water quality in the water supply tank (new smooth surfaces in the storage reservoir and the possibility of the easy cleaning during the operation of two chambers), and

(3) The mitigation of the likelihood of air contamination of the drinking water (casting of the elements for the air filtration that flows into the water reservoir)

(4) The mitigation of the consequences of a possible targeted attack on an object (the detection of the entrance to the building, increasing of the security)

(5) The mitigation of the consequences of a possible failure of the pipes with a massive water leak (casting of the automatic valve at the outlet pipe of the water tank).

In a similar manner all proposed measures were assessed in terms of their investment and future operating costs. The measures were combined into four phases (points A, B, C, D and E in the graph of Fig. 7) and their total cost is 3.3 million EUR (8.8 mil. CZK) A gradual implementation of all measures would gradually mitigate the accumulated value of the risk in the whole system to a targeted value of 25. In the system the undesired events will be consciously tolerated which generate low risks of the category K1. This information is inserted back into the software application and simultaneously simulates their effectiveness in mitigating the risks. I.e. for each measure the information will be complemented that will eliminate the undesired events and which will provide a new value of the consequences and likelihood of the given undesired event after the implementation of new measures. The simulation result is shown again by a risk matrix analogically as it is illustrated in Fig. 6. Another useful outcome of this simulation is the following graph which shows the dependence between the amount of costs to mitigate the risks in the system and the accumulated value of the risk in the system.

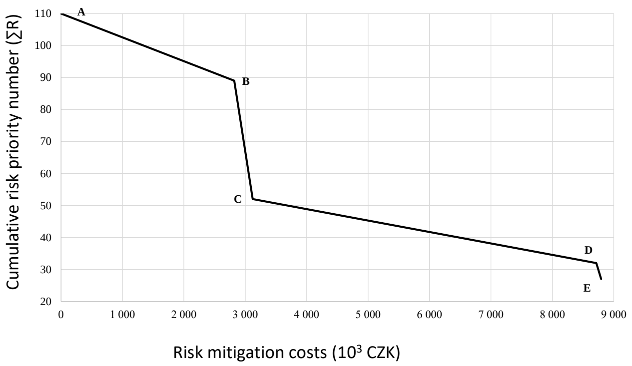

Figure 7. The value of the cumulative risk priority number in the WSS depending on the amount of costs given for the risk mitigation

The line connecting the points from A to E in the graph in Fig. 7 shows the dependence of cumulative value of the risks on the amount of the invested costs to mitigate them. Points from A to E correspond to the condition of the system after the implementation of measures in the phase from I up to IV and the corresponding costs. To illustrate this, the first phase of implementation of remedial measures, which can be introduced, is the construction of a new water supply tank. Measure requires a one-time investment of 2.8 million CZK and guarantees the reduction of risks from point A (110) to point B (89).

4 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 the risk generated by floods at a different frequency-rate. In the water-supply sector, the first idea of the HACCP principle implementation appeared in 1994. 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. Currently the methods and principles of risk analysis in the field of water supply are a well-established legitimate instrument, which is also determined by a valid legislation.

On the example of a simple public water supply system of the small village within the possibility of the scope of this paper the whole process was demonstrated, how to use the existing methods and risk analysis tools for risk management in water supply systems.

REFERENCES

[Brezina 2011] Brezina, T., Kovar, J., Modeling and control of system with pump and pipeline by pole placement method. Proceedings of 14th International Conference on Mechatronics, 2011, art. no. 5961082, pp. 6-9.

[CSN IEC 300] Reliability management – Risk analysis of the technological systems, Praha, Cesky normalizacni institut, 1996, (in Czech)

[Davison, A.] Water safety plans: managing drinking-water quality from catchment to consumer, World Health Organization, Geneva, 2005.

[Tuhovcak, L et al.] WaterRisk – Risk analysis of the public water supply systems. 1. 1. Brno: Published by CERM, 2010. 254 s. ISBN: 978-80-7204-676- 8

[Tuhovcak, L.] Taus, M., Kucera, T., The assessment of the technical condition of the water distribution systems, (2014) Procedia Engineering, 89, pp. 1420-1427

[Tuhovcak, L.] Profil interview, Water management (in Czech) , 5/2016, pp. 17-19, Ckyne, CR, 2016, ISSN 1211-0760

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