Fault tree analysis as a tool for risk assessment and its use for Infrastructure Asset Management in water utilities

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Sammendrag

Hovedmålet for vann- og avløpsselskaper er å forsyne brukerne med tilstrekkelig og kvalitetsmessig sikkert vann når de trenger det og å beskytte miljøet ved å rense avløpsvannet til et tilfredsstillende nivå. Måloppnåelsen kan bli hindret ved at feil i VA-systemene både kan gi dårligere forsyningssikkerhet og forringet kvalitet på vannet. I denne artikkelen er bruk av feiltreanalyser for risikovurdering av vann- og avløpstjenestene drøftet. Det er også vist noen eksempler på anvendelse.

Abstract

The primary goals of water and wastewater utilities are to provide safe and secure drinking water to their customers every time they require it, and to protect the environment by treating wastewater to an acceptable level. These might be easily affected due to the fact that water systems are prone to structural damages that can change the quantity and quality of the delivered water. Because of the nature of the service provided, there is no room for errors as they could have an important negative impact on the health of consumers and the environment. In this paper, the use of Fault Tree Analysis as a tool for risk assessment in water and wastewater utilities and its use for Infrastructure Asset Management will be discussed and some examples of its implementation will be introduced.

Introduction

The primary goals of water and wastewater utilities are to provide safe and secure drinking water to their customers every time they require it and to protect the environment by treating wastewater to an acceptable level. The delivered water has to be safe in microbiological and chemical terms and has to have an acceptable physical appearance. Such conditions can be easily affected due to the fact that water systems are very prone to structural damages that can change the quantity and quality of the delivered water. Increasing consumer demand and infrastructure ageing are examples of factors that can affect the service provided by water utilities. Due to the nature of the service provided by these installations, there is no chance for errors as they could have an important negative impact on consumer health and the environment. This is why it is very important for managers in the water industry to identify the various hazardous events that might have an influence on the service, and the associated risks.

The International Organization for Standardization (ISO) has some frameworks for risk management that can be used by any type of organization as they show the principles, guidelines, terminology and processes that have to be adopted to manage risk properly (ISO 31000:2009, ISO Guide 73:2009 and ISO/IEC 31010:2009). Risk analysis plays an important role in risk management decisions. In many industries (like pharmaceutical, food, medical and chemical), risk analysis of their final products or of certain components in their products are conducted in order to reduce the risks of harm to a minimum in case of consumption of a particular food or drug. Nowadays, manufacturers address the risk of their products to humans and the environment taking into account a lifecycle approach in which they consider the whole production process (cradle-to-grave). Also, risk analysis strategies now have a broader application in different utilities, such as petroleum refineries or hydrogen plants[1, 2]. Its recent application in water utilities is based on the protection of public health from contaminated water.

In the last decade, several frameworks based on risk assessment have been created and applied in water utilities to guarantee water safety. In 2004, the World Health Organization published the "Guidelines for Drinking-water Quality" which were drawn to support the development and implementation for risk management strategies in order to ensure the safety of drinking water supply [3]. The guideline focuses on the development and application of water safety plans using risk tools to prioritize risk management measures. By conducting risk analyses, the utility managers might be able to lower the risks associated to hazardous events and achieve an acceptable level using risk reduction measures; this is also known as risk management. But what is risk analysis? What are the tools which can be deployed to carry one out?

Risk assessment in utilities

The concepts of hazard and risk need to be fully understood in order to grasp what a risk analysis is. A hazard is a situation or substance that has the potential to cause harm while risk is the likelihood or probability of a certain undesired event to occur within a certain period of time or under specified circumstances[4]. Risk is a function of the probability of an event to happen and the consequence of such an event. Risk assessment is a process where hazards for a certain process are identified, then, the risk associated to those hazards is analyzed and evaluated in order to determine appropriate ways to eliminate or control them using risk reducing measures, see figure 1. This type of assessment helps to understand how accidents can occur by answering questions like: *What can go wrong? How bad could it be? How often could it happen? And is that acceptable?*

First, the hazards in a certain process have to be determined. The people in charge of doing the risk assessment ought to have a complete knowledge of the systems, be familiar with the work area and have an understanding of the different problems that might be found during the operation of the system. It is recommended that the team should be formed by water works experts (operators, planners, lab personnel, etc.) and external specialists (researchers, consultants, etc.) who have a different level of complementary expertise.

Then, the risk of the hazard or event needs to be analyzed and for that the probability and consequence of the hazard needs to be calculated. A qualitative or quantitative approach can be used depending on the amount of information available. Nowadays, there are different tools that can be used to compute the probability of a hazardous event, like the Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA), Reliability Block Diagram (RBD), among others. Examples of tools to determine the consequence of an event are: Event Tree Analysis (ETA), Cause-Consequence Analysis, FMECA, among others. After the risks (probability and consequence) of the events are determined, they can be evaluated by using a probability scale and a consequence dimension scale to create a risk matrix. This risk matrix will help prioritize events that have a non-acceptable level of risk on which

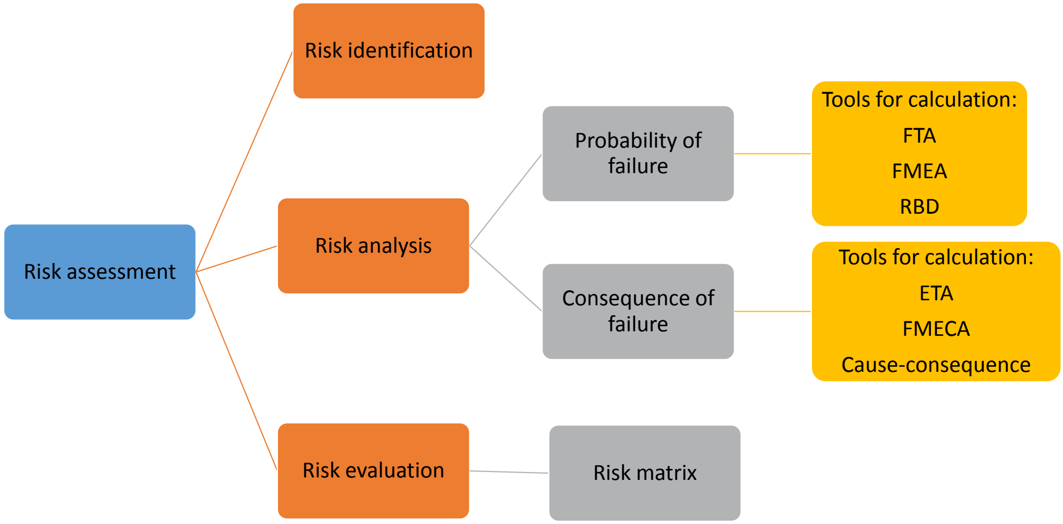

Figure 1. Risk analysis flow chart.

immediate actions needs to be taken to minimize it. This level of risk acceptance has to be defined by the people in the water utilities based on different standards and directives[5].

As stated before, Fault Tree Analysis (FTA) is a tool that helps to identify the probability of occurrence of an event, and it also shows the possible ways by which a hazardous event may arise. In this article, the use of Fault Tree Analysis in water utilities as a tool to calculate risk will be discussed.

Fault Tree Analyses in water utilities

A FTA is a logical and diagrammatic tool that helps to estimate the likelihood or probability of an event to occur based on the occurrence or non-occurrence of other events[6, 7]. While performing an FTA, it is important to define the boundaries of the system that is going to be analyzed and the objective of the analysis should be phrased in terms of failure of such a system [8]. The FTA is more suitable for component analysis like pumping stations or treatment plants; it can also be used to analyze networks, however, the analysis is far more complex and complicated.

In order to carry out a FTA a main or top event has to be determined; this top event is a critical situation that can cause the system's failure or it's the system failure itself. The tree formation starts with the definition of the top event, then the events that may lead to the top event are identified and connected to the top event with a logic gate. Further, the events leading to each immediate event are identified and connected with logic gates. This process continues until all the basic causes of the top event are identified, see figure 2. A FTA is a binary analysis, which means that all events can either hap pen or not (there are no other options) and also, an FTA may be qualitative, quantitative or both depending on the information available and the goals of the analysis. For more information about how to make an FTA see [9].

Why use FTA in water utilities? Some of the advantages of this analysis are that it helps to have a complete understanding of the system and how the failure relationships work in it. Also, the identification of weak points in the system is possible, enabling managers to optimize operations by prioritizing the contributors leading to a top event and taking actions to avoid them. The latter would help to optimize and minimize the resources by focusing on the parts of the system that are really critical for the process. FTA can also help to identify the causes

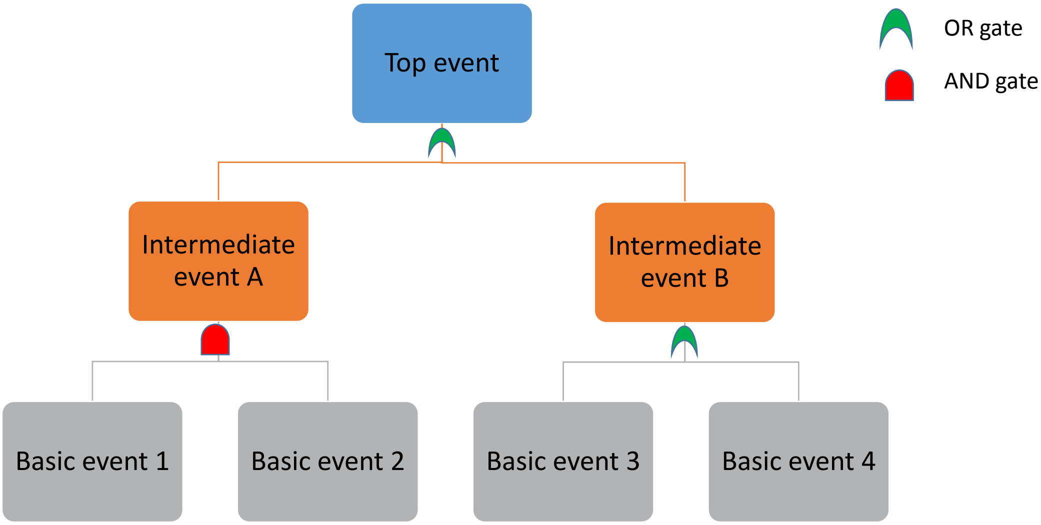

Figure 2. Example of a fault tree [10].

of a failure in the system and evaluate how a basic event contributes to the top event[2, 7]. Plus, it allows the consideration of events of different natures - mechanical, operational or natural.

An FTA can be used together with reliability data of the basic events to make a rough estimation of the system's reliability; when the top event is the system's failure, then the basic events are normally component failures[11]. Minimal cut sets, which are the smallest collection of basic events that result in the occurrence of the top event, can be identified and used to understand the structural reliability of a system; the longer the minimal cut set is the less vulnerable the system is to that group of events. Also, if one event in the minimal cut set is removed, then the top event won't happen[12].

However, this method can be very time-consuming and vulnerable to human error. This is because a lot of detailed information on how the system is formed, works and behaves is required when a qualitative approach is adopted. When a quantitative approach is being used, even more information is required since the probability of occurrence of the basic events is needed in order to calculate the probability of the output or top event. It is important to mention that it is very difficult to estimate precise failure probabilities of the basic events of an FTA because the available data are normally insufficient. The lack of data is one of the biggest problems in the water and wastewater sector because data recording can be time-consuming and expensive for the utilities To overcome the lack of information, rough estimates can be used by applying a hybrid approach of a fuzzy FTA to evaluate the probabilities of the different events and estimate an overall system failure probability [7]. Nowadays, there are some computer programs, like PROFAT II, that help construct and calculate the failure probabilities of a fault tree which makes the process quicker and simpler [13, 14].

Additionally, a conventional FTA doesn't monitor the probability of the top event as a function of time and so, depending on the characteristics of the system being analyzed, a different analysis must be done after a certain period of time. Water and wastewater utilities are prone to frequent changes over time because the internal and external conditions of the asset may vary due to several factors such as infrastructure ageing for example. It is important to point out that significant training and experience is also necessary to be able to use an FTA correctly, since the success of making one strongly depends on the skills of the analyst[9].

The use of FTA for risk assessment could help in the implementation of Infrastructure Asset Management (IAM) in water and wastewater utilities. IAM is a set of coordinated activities with which an organization can manage their physical assets at a minimum level of risk and cost while having a good performance. In order to determine the actual state of the system and to plan the actions that will allow meeting the desired levels of risk, cost and performance, management needs to conduct different economical, reliability and risk analysis. Given the complexity of describing system failures and assessing their probabilities, logic models like FTA are used to carry out the risk analysis. There are different levels at which IAM can be planned: strategic (long-term), tactical (medium-term) and operational (short-term). These levels are always connected and have a consecutive flow - strategic plan (Why?) tactical plan (What?) and the operational plan (How?) The use of FTA for risk analysis can help in the implementation of IAM in water and wastewater utilities at an operational level, since the scope at this level is to plan and implement actions or measures in a group of components over the short-term, that will aid and/or ensure the asset's operation[15]. Given that the implementation of IAM seeks to balance spending with risk minimization, it is important to identify, analyze and prioritize critical assets going from a process to a component level [16]. By using FTA, water utilities managers can be prepared for a potential hazard by taking precautionary actions, generate quick response plans for events that can damage the system's performance and create monitor and maintenance plans.

Examples of implementation of FTA in water utilities

Even though the use of an FTA has its limitations, it has shown to be an effective tool for risk analysis that can potentially benefit the implementation of IAM in water utilities. Ugarelli and Røstum in [5], has shown the use of an FTA in a large pumping station located in the western part of Oslo. The objective of the FTA was to obtain a detailed analysis of the station and get an understanding of how an undesired event could take place based on a coarse risk analysis done previously by the authors. The top event in this study was the pumping station's failure to function; 36 first-order cut-sets (only one component failure or event is required for the system's failure) and 4 second-order cut-sets (two component failures or events are required) were identified with a qualitative approach. A quantitative approach was also used; the unreliability of each component was determined by using the ratio of the mean time to repair the component and the mean time to failure of the component. With this, the top event probability was calculated and the events that contribute the most to the failure of the pumping station were found using Birnbaum's importance measure. In the case of some of the events, it was fire leading to failure at the electrical cabinet and sabotage, among others. At the end, risk-reduction actions were proposed by the analysts to the water utility to control the most important events, e.g. the installation of fire extinguishers. The study proved that FTA is a good tool to identify critical events that contribute the most to the system's failure and can be also used to evaluate risk-reducing measures that could increase the reliability of the pumping station.

Another example is the FTA done in [12], where the authors made a qualitative FTA for a drinking water plant to understand the technical and operational hazards at the treatment plant that could increase the risk of infection from pathogens. The plant consisted of the following processes: screening, coagulate dosing and mixing, mechanical flocculation, submerged ultrafiltration and chlorination. The FTA covered the physicochemical part of the treatment (from screening to UF). They defined their top event as the presence of unexpectedly high concentration of *Cryptosporidium parvum* in the permeate, and the tree was constructed based on the operators' knowledge and literature review. They found 19 different basic events and 16 minimal cut-sets.

They realized that the majority of the minimal cut sets were related to the membrane filtration process itself. This was due to the fact that the processes upstream have less influence on the removal of pathogens in the water. They compared their results with a FTA done in a conventional WTP and found out that there are more failure paths in the conventional plant than in their own. They concluded that the FTA helped in the identification of potential hazards and summed them up in a concise and logical diagram that was easy to understand and helpful in evaluating the preparedness of the treatment system to harmful events[12].

An example of a more complicated use of FTA in water utilities is the one that was carried out by [6] in Gothenburg, Sweden. In this study, an integrated probabilistic risk analysis was done in a large drinking water system using FTA; the entire drinking water system was analyzed (from source to tap). The main source of water in Gothenburg is a river and a couple of lakes; the system has 2 WTPs and a distribution network, 1700 km in length. The whole system was divided into 3 subsystems: raw water, treatment and distribution. The top event selected was water supply failure, and this failure was determined based on both the quantity and quality of water delivered in each subsystem, see figure 3.

Because supply failures in one subsystem can be compensated by other parts of the system, they had to use two variants of the AND logic gate when constructing the FTA: one was designed for situations where the ability to compensate was limited by time and the other one was used when the ability to compensate may recover after the system failed. The first one could be used, for example, when insufficient raw water is compensated by the reservoirs in the treatment plant or the distribution system, and the second one can be used when unacceptable raw water quality is compensated by treatment. The failure events and the structure of the tree were

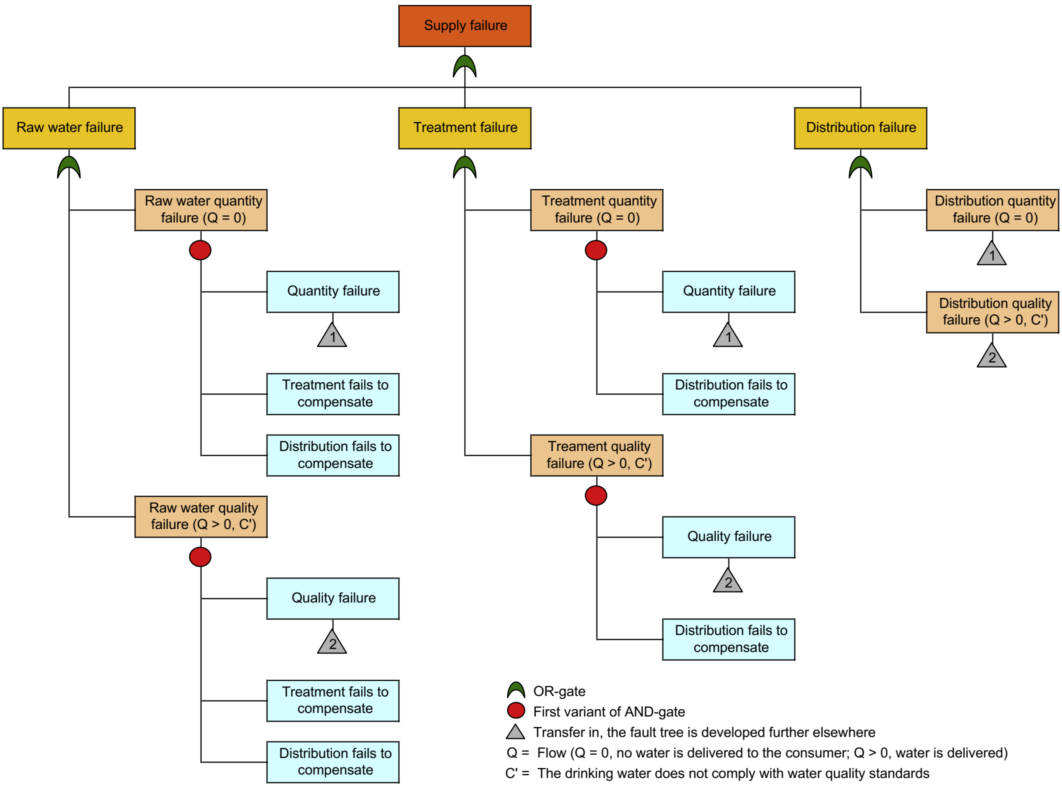

Figure 3. FTA for drinking water system[6].

drawn up in collaboration with people from the water utility in Gothenburg. In all, 116 basic events and 100 intermediate events were found.

In this case, the risk of the top event was calculated as the sum of the risks of the different events in each subsystem (raw water, treatment and distribution) for quantity and quality failure. For this, the probability and consequence of failure in each subsystem was calculated. The probability in each subsystem was determined using the mean failure rate and mean downtime of each event under the subsystem. The consequence in each subsystem was calculated as the duration of the failure and the number of people affected by each event under the subsystem (Customer Minute Lost). At the end, the result showed that the total risk level in the system is mainly due to raw water failures in both, quantity and quality failure. They found that this was due to the fact that a large number of people are affected by this and also that the downtimes are quite long. The probability of raw water failure is low but when a failure occurs the mean downtime is long and many people are affected. The treatment subsystem has a low failure rate, short mean downtime and little impact on the total risk. The distribution system has frequent failures but a very short mean downtime, and thereby, relatively few people are affected. This represents little impact to the total risk of the event [6]. They showed that is possible to use an FTA to create an integrated risk analysis in the drinking water system considering the compensation from other parts of the system, but some modifications and adaptations need to be done when developing the fault tree.

Conclusions

The studies of FTA usage in water and wastewater utilities have been scarce. However, some studies have shown that the use of FTA for risk analyses is very valuable for water utilities since they help to understand the system's behavior and how failures can happen. They can also help to identify cut-sets and weak points of the process, and thus managers can optimize operations by prioritizing the contributors leading to a top event and taking actions to avoid them. They can also create a checklist for maintenance purposes that focuses on these critical parts.

However, to be able to create a good analysis, there should be enough available data. This might be hard in water and wastewater utilities since data is mostly not recorded. One of the good things about FTA is that different approaches can be used depending on the amount of data available. Also, the FTA should be done in close collaboration with the operators at the water utilities, to get as much information as possible. A good recommendation to water utilities that do not have enough data is to start investing in its collection in order to be able to realize analysis that will help to improve their performance and decrease the level of risk in the installations.

When using FTA, it is important to define the boundaries of the system being analyzed. FTA can be applied to components in water utilities, such as pumping stations and treatment plants, however, it can also be used to analyze water systems from source to tap as shown by [6]. FTA can be an important tool to make risk reduction decisions and support decision-making in water and wastewater utilities which can aid in the implementation of Infrastructure Asset Management. It is important to encourage its use in this type of facilities, since it has shown to help in the understanding of the development of failures, and it might be useful in creating quick response plans to hazardous events.

References

1. O. Rosyid, D.J.a.U.H., *Risk analysis for the infrastructure of a hydrogen economy.* International Journa of Hydrogen Energy, 2007. **32**(15): p. 3194-3200.

2. D. Wang, P.Z.a.L.C., *Fuzzy fault tree analysis for fire and explosion of crude oil tanks.* Journal of loss prevention in the process industries, 2013. **26**(6): p. 1390-1398.

3. WHO, *Guidelines for drinking-water quality.* Vol. 1. 2008, Geneva: World Health Organization 668.

4. Pollard, S.J.T., *Risk management for water and wastewater utilities.* Water and Wastewater Technologies. 2007, United Kingdom: IWA publishing. 172.

5. Ugarelli, J.R.a.R., *Integrated Urban Water System*, in *Risk and Interdependencies in Critical Infrastructures: A guideline for Analysis* 2012, Springer: New York.

6. Andreas Lindhe, L.R., T. Norberg and O. Bergstedt, *Fault tree analysis for integrated and probabilistic risk analysis of drinking water systems.* Water research, 2009. **43**: p. 1641-1653.

7. P.V. Suresh, A.K.B.a.V.V., *Uncertainty in fault tree analysis: A fuzzy approach.* Fuzzy sets and Systems, 1996. **83**: p. 135-141.

8. P. Hokstad, I.B.U.a.J.V., *Risk and interdependencies in critical infrastructures: A guideline for analysis.* Springer series in reliability engineering. 2013, New York: Springer.

9. Høyland, M.R.a.A., *System Reliability Theory: Models, Statistical Methods and Applications.* 2nd edition ed. 2004, New Jersey Wiley-Interscience.

10. Lindhe, A., *Integrated and probabilistic risk analysis of drinking water systems*, in *Department of Civil and Environmental Engineering.* 2008, Chalmers University of Technology Göteborg.

11. Cooke, T.B.a.R., *Probabilistic Risk Analysis: Foundations and Methods.* 2001, New York: Cambridge University Press.

12. N. Beauchamp, B.L.a.C.B., *Technical hazard identification in water treatment using fault tree analysis.* Canadian Journal of Civil Engineering, 2010. **37**(1): p. 897-906.

13. A. A. Baig, R.R.a.A.B.B., *Reliability analysis using fault tree analysis: A review.* International Journal of Chemical Engineering and Applications, 2013. **4**(3): p. 169-173.

14. Abbasi, F.K.a.S.A., *Analytical Simulation and PROFAT II: a new methodology and a computer automated tool for fault tree analysis in chemical process industries.* Journal of Hazardous Materials, 2000. **75**(1): p. 1-27.

15. M. A. Cardoso, M.S.S., S. T. Coelho and M. C. Almeida, *Urban water infrastructure asset management- a structured approach in four water utilities.* Water Science and Technology, 2012. **66**(12): p. 2702-2711.

16. B. MacGillivray, P.H., J. Strutt and S. Pollard, *Risk abalysisi strategies in the water utility sector: an inventory of applications for better and more credible decisionmaking.* Critical Reviews in Environmental Science and Technology, 2006. **36**(2): p. 85-139.