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Safety analysis of water supply systems including protection barriers

Keywords

water supply system, protection barriers, event tree

Abstract

Water quality control from the perspective of water supply system users' safety contributed to create drinking water production and quality control procedures. Contemporary risk hazard analysis should be performed on the stage of production, distribution and storage of tap water. Sequences of undesirable events are considered in the so-called waterworks chain series. This leads to critical control points and gives the ability to provide current control over the processes in the collective water supply system, as well as of their combinations and mutual interactions. Methodology of water consumers protection against incidental pollutions was shown. Algorithm concerning identification of critical control points - CCP was developed .The rules of safety related system into drinking water production have been shown. Also risk assessment using the tree event method was presented.

1. Introduction

Collective water supply system (CWSS) consists of functionally interrelated subsystems, such as: water intake, water treatment, pumping, transmission and water distribution subsystems. The particular subsystems and their objects are an interdependent integral whole and their goal is to provide consumers with drinking water, in accordance with the requirements of reliability and safety. Water supply systems belong to critical infrastructure along with other systems crucial for national and local communities safety.

Already in 2004 the World Health Organization (WHO) highlighted the strategic importance of CWSS in the context of safety of public health, recommending the implementation of the so-called Water Safety Plans [19], [21]. A new standard in the widely understood water management are the so-called Water Cycle Safety Plans (WCSP), which includes an analysis of all the possible risks related to the circulation of water in nature [20], [22]. Additionally, the WCSP introduce safety analysis not only in the context of water consumer safety, but also the so-called environmental safety aspect.

There are two basic types of threats to CWSS [16]:

- endogenous - a source is inside the system and can be controlled (resulting directly from the CWSS operation, e.g. damage of system components, failures of water mains or distribution pipes and fittings, failures of pumping stations)
- exogenous - a source is outside the system, and thus the system operator cannot control it, e.g. accidental contamination of water source, the forces of nature, such as flooding, drought, rainfall, storms, landslides, as well as the lack of power supply and the acts of third part - vandalism, terrorist attack, cyber terrorist attack .

Collective water supply system vulnerability to threat is associated with [16]:

- operational reliability of particular objects and equipment,
- failure removal efficiency,
- structure of connections of individual elements of water supply network and equipment and methods of reserve,
- mobility of water treatment technology and even periodic introduction of its alternative variants,
- a number of water sources (e.g. intakes of surface and underground waters).

Collective water supply system protection against threats is associated with [9]:

- water quality monitoring and response to poor water quality, such as: early warning - protection stations of water intakes,
- water intake protection zones,
- monitoring and management of hydraulic parameters of water supply network,
- disposal of a volume of assurance in clean water tanks,
- alternative ways of drinking water supply in crisis situations,
- professional risk management.

2. Safety of collective water supply systems

Safety is defined as characteristics of a system that shows its resistance to the dangerous situations (threats), with attention focused on the unreliability of system safety (vulnerability to the dangerous situation) [23].

At the macro level, safety concerning water supply is defined as a state of water management that allows to cover current and future customers demands for water, in a technically and economically justified way, and by the requirements for the protection of the aquatic environment [7].

With regard to drinking water consumers, safety is defined as the likelihood of avoiding the threat arising from the consumption of water with quality incompatible with the existing regulations or the lack of water [11], [12].

Threats to CWSS arise at each stage of drinking water production, that is from a source of water through water treatment, storage, pumping and distribution.

Threats to water source are primarily the result of:

- unfavourable meteorological factors (floods, droughts),
- incidental impurities from point discharges of urban or industrial waste water, waste or other substances, as well as random catastrophic events,
- agricultural activities (fertilizers, livestock waste),
- incidental impurities.

It is advisable to identify these threats [1]. The next step is the assessment of risk associated with these threats, the introduction of control measures to minimize the risk [5], [15].

Protection of water intakes is primarily provided by:

- determining the so called water intake protection zones (in accordance with applicable regulations),
- monitoring of raw water quality in the source, e.g. by using the so called water intakes protection stations. They are container stations, located above the water intake, in which the basic raw water quality parameters are continuously and automatically measured (among others pH, turbidity, dissolved oxygen, ammonia nitrogen, organic carbon, hydrocarbons), and the data are transmitted to the central control room.

If harmful, not removable in the process of treatment contaminants, were not detected, contaminated water may be taken and, as a result, water that does not meet the relevant criteria will be produced [6]. When contaminated water is taken and contamination is detected with a delay (e.g, in treated water) water supply objects will be contaminated. In both cases, you may need to rinse the equipment of technological line or disinfect the network. In this way, any incidental contamination of the raw water is immediately identified by the system operator, and it is possible to protect the water intake [2], [4], [18].

Threats at the stage of water treatment in the water treatment plant (WTP) are primarily the result of:

- improperly selected treatment technology,
- failures of a particular equipment for water treatment.

Protection during water treatment is primarily provided by:

- water quality monitoring at each stage of water treatment,
- alternative water treatment systems.

Threats during storage, pumping and distribution of water are primarily the result of:

- failure of water pipes and fittings,
- secondary water pollution in the water network,
- incidental events causing lack of water supply to the distribution subsystem (e.g, pollution of water sources, water treatment plant failures, contamination of water in network tanks)
- water pump failures.

Protection at this stage is performed by:

- ensuring the protection of critical elements,
- remote monitoring.

Monitoring of water supply network is a system of measurement and analyses of functional and technical state of the network, in order to obtain a reliable basis for managing the operation of the network and its modernization. The planning and execution of the full monitoring of the water supply network can be divided into the following stages of action [9]:

- choice of measurement parameters,
- for quantitative measurement: flow rate, pressure and, if necessary, water level in the tanks,
- for the measurement of water quality: the possibility of using different parameters representative to assess the quality, depending on the material of pipe and fittings, safety of handling, etc. should be analysed,
- choice of measurement points location,

– choice of methods and measuring equipment,
– determining the required frequency and time of measurement,
– construction of measuring stations and calibration of devices,
– measurement registration, archiving and transmission of results,
– creating service team and its training,
– establishing procedures for the access to the system and the use of measurement results.

Methodology for the determining the measuring points for water quality examination should take into account the possibility and the speed of detection of water pollution on a given level, the representativeness of the results, the retention of water in the network, the impact of pipes on water quality. The choice of the measurement point of water quality in the distribution system is a very complex problem and its solution requires not only detailed analyses of the water supply network and the conditions of its operation, but also the analysis of water quality parameters. The extent of monitoring, full or simplified, continuous or laboratory, is also important.

Indicator organisms, the so-called biomonitoring, are used in CWSS to assess water quality of both taken and treated water. For this purpose, the toxicity level of water is determined, based on short-term culture called biotests, or a continuous long-term observation is carried out, recording aquatic organisms behaviour, the so-called biomonitoring, the purpose of which is to signal potential contamination of water intended for human consumption. The examples are certain species of fish, mussels and even certain species of microorganisms.

3. Analysis of the safety related system

In the safety issues of CWSS one distinguishes the system ensuring the safety called Safety Related System (SRS), based on the Independent Safety Layers (ISL) The ISL consist of the independent protection barriers, called the Independent Protection Layers (IPL) and the independent barriers that mitigate the consequences of failure, called the Independent Mitigation Layers (IML). Multi-layer safety system has a serial structure and when a lower barrier performed the task successfully, there is no need to run a higher barrier.

The IPL consist of:

– Barrier 1 (IPL1) - the so called early warning system, when the raw water samples are taken at its source and an operator receives the information about water quality in advance, which allows him to make appropriate decisions and implement them (to prevent that contaminated water enters the raw water subsystem),
– Barrier 2 (IPL2) - the delayed warning system, when the treated water samples are taken in the water supply system and it is possible to stop the flow of water to the water distribution subsystem (WDS),
– Barrier 3 (IPL3) - the late warning system, the treated water samples are taken in water distribution subsystem (based on it people can be warned against identified threat and the use of tap water, via radio, television, leaflets, announcements from the car sound apparatus, etc.).

The IPL operation is shown in *Figure 1* [9].

Making appropriate process decisions or a decision on warning people always require to get information ahead of time. The earlier the water supply system operator receives the information about the threat, the bigger is the possibility to make right decision. Decisions are often made under conditions of uncertainty. If harmful quality water gets into system, it can mean the loss of safety, that is, serious health problems among the population and, in extreme cases, death. However, if the incidental contamination in the water source is detected early enough, the consequences can be insignificant and it can only lead to a periodic interruption of work of subsystem components or periodic decrease in subsystem efficiency [10].

The IML system consists of:

– IML 1 - the integrated information system, including the system of warning people about the threat associated with the so called water safety,
– IML 2 – the response plans in a crisis situation, including the possibility to supply drinking water from the alternative sources, the development of the so called maps of risk in CWSS,
– IML 3 – the so called water safety plans, based on an analysis of risk arising from the possibility of the occurrence of undesirable events in all the CWSS subsystems.

The critical control points (CCP) are places in which to ensure the safety of water supply network the control and the possibility to take the preventive measures in order to eliminate risk of threat or to minimize it to a tolerable level are necessary. The identification of the critical control points is performed using the decision tree analysis. This methodology involves asking a sequence of questions and getting answers in the form of yes or no, related to the elimination of the given threat or its minimizing to a tolerable level. In this way, the decision is made whether the given stage is the critical point or not. *Figure 2* shows the procedure

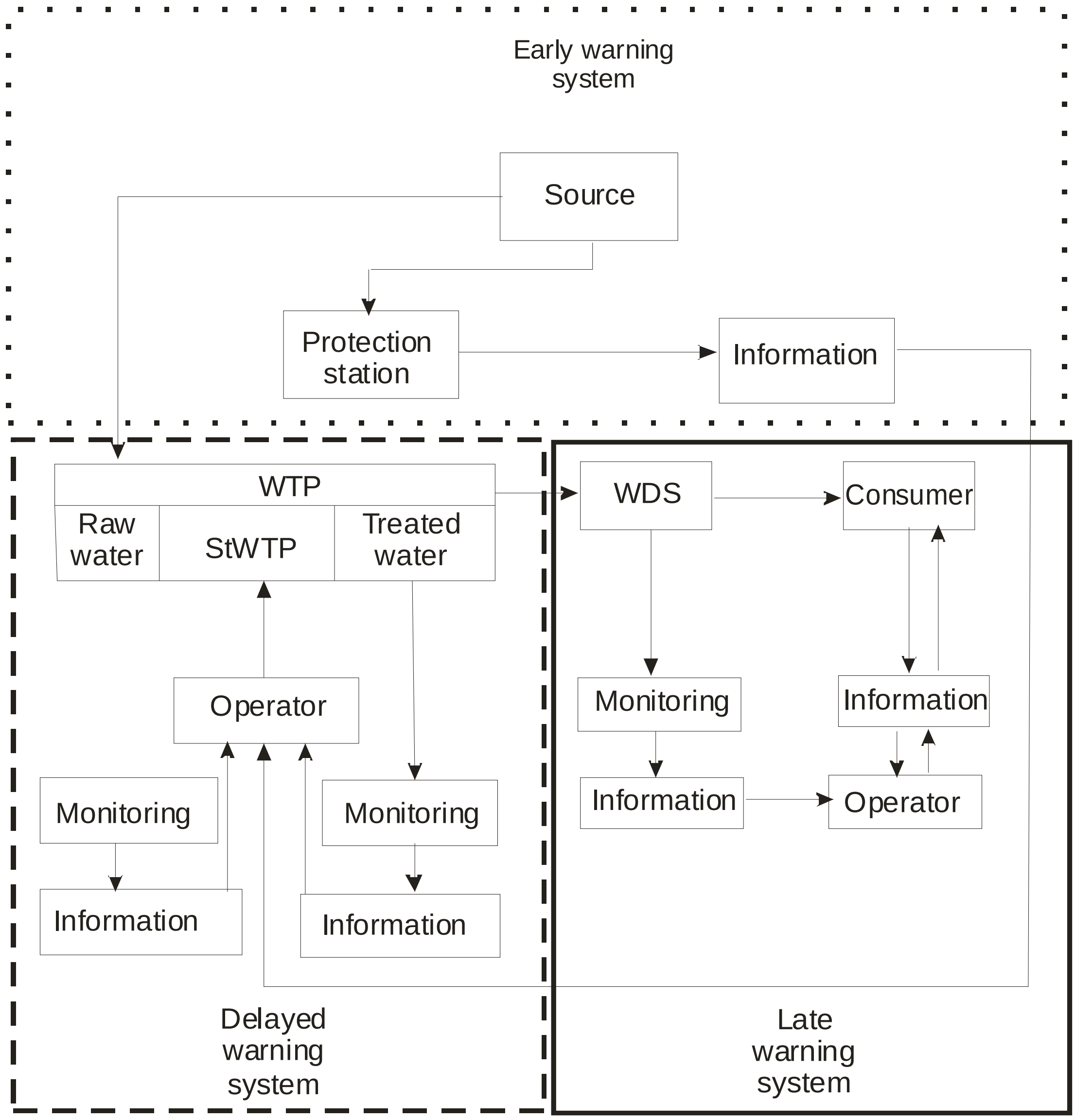

Figure 1. The warning system against harmful quality water

for determining the CCP using the decision tree [10]. The required monitoring points are shown in *Figure 3* [14].

3. Safety analysis of CWSS using the event tree method

The logic tree methods are often used to analyse risks associated with CWSS operating [17]. They rely on recording the cause and effect relationship using special logic symbols. The most often to analyse the probability of undesirable events occurrence the so called fault tree method (FTA) is used [3], but the consequences are mainly analysed using the event tree method - ETA [8]. The comprehensive risk analysis is performed using a hybrid method described in details in [13]. Both the event tree method and the fault tree method require, on one hand, a specific systemic view of the problem, and, on the other hand, thorough knowledge of the construction of the analysed subsystem.

The event tree analysis examines the way from the initiating event through the different scenarios of using particular protections until the final consequence of this event. In contrast to the fault tree analysis, which is deductive, the event tree analysis is inductive. In many cases, a single event can have different consequences (disaster, major failure, failure, controlled dangerous situation), depending on the possibility of an emergency scenario development (multi barrier system is activated or not activated). At each stage of the creation of tree the appropriate values of the probability of activation or lack of activation of the ISL are determined. For CWSS it will be the analysis of the IPL and the IML.

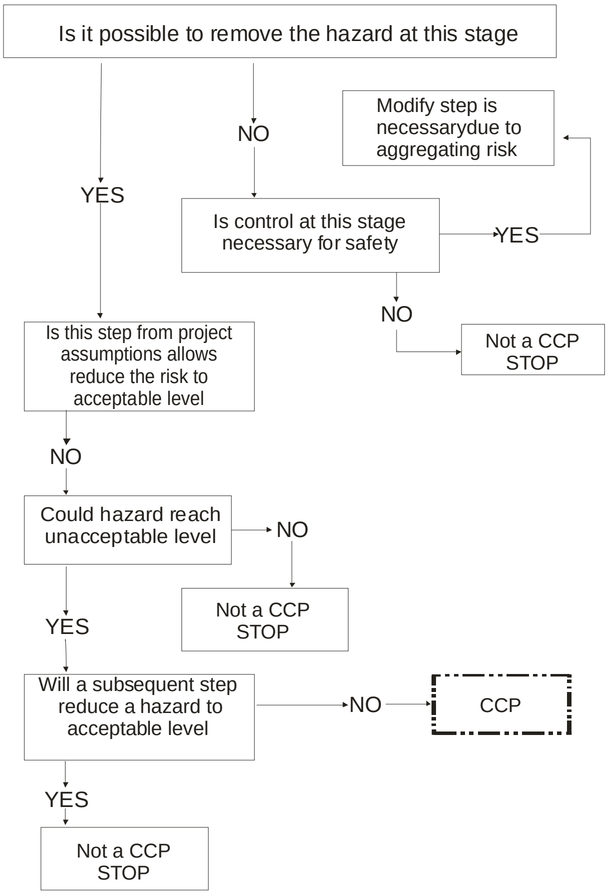

Figure 2. Identification of the CCP

In the event tree quantitative analysis it is necessary to determine the probability of activation *(Pi)* or lack of activation *(1-Pi)* of the individual barriers [3]. Quantitative assessment of the event tree means determining the probability of the output event. The probability *Pi* is assigned to the branches representing the success (1) and the probability *1-Pi* to the branches representing the failure (0). Therefore, the sum of the probabilities on every branching must be 1. The particular probability of the output events is obtained by multiplying the probability on the given path - from the input event to the output event. The tree diagram for the analysis of scenario after the initiating event *X* - contamination of water source, is presented in *Figure 4*.

In the presented event tree (*Figure 4*) we obtained:

– the probability that the situation P_1 will be under control (no threat):

$$P_1 = P(X) \cdot P(\mathrm{IPL1}) \qquad (1)$$

– the probability of failure P_2 (little threat):

$$P_2 = P(X) \cdot [1 - P(\mathrm{IPL1})] \cdot P(\mathrm{IPL2}) \qquad (2)$$

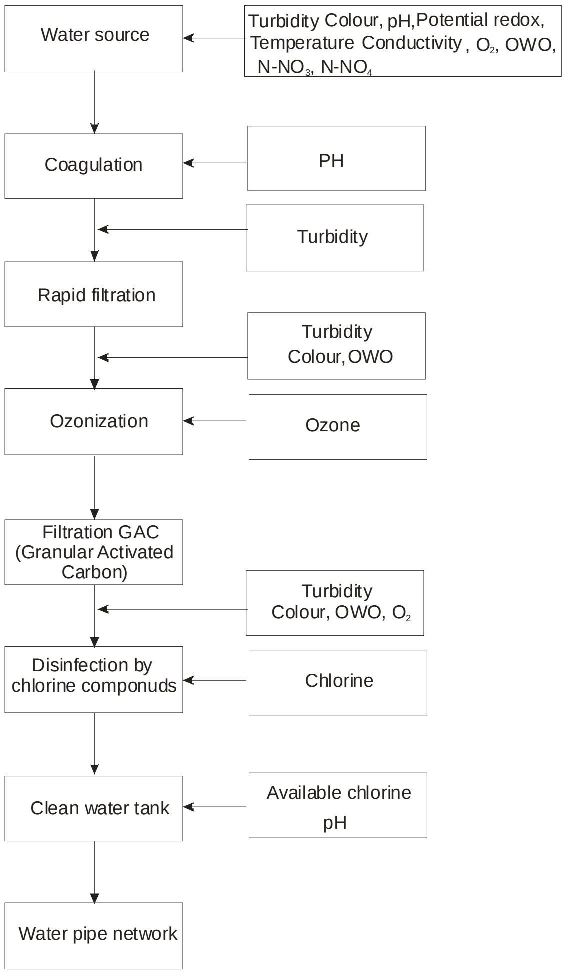

Figure 3. Control points in technological process

– the probability of a major failure P_3 (medium threat):

$$P_3 = P(X) \cdot [1 - P(\mathrm{IPL1})] \, [1 - P(\mathrm{IPL2})] \cdot P(\mathrm{IPL3}) \qquad (3)$$

– the probability of disaster P_4 (large threat):

$$P_4 = P(X) \cdot [1 - P(\mathrm{IPL1})] \, [1 - P(\mathrm{IPL2})] \cdot [1 - P(\mathrm{IPL3})] \qquad (4)$$

It should also be noted that the sum of the probabilities of the output events must be equal to the probability of the input events:

$$P(X) = \sum_j P_j \qquad (5)$$

where: j – a number of the output events, in the analysed case j = 1, 2, 3, 4.

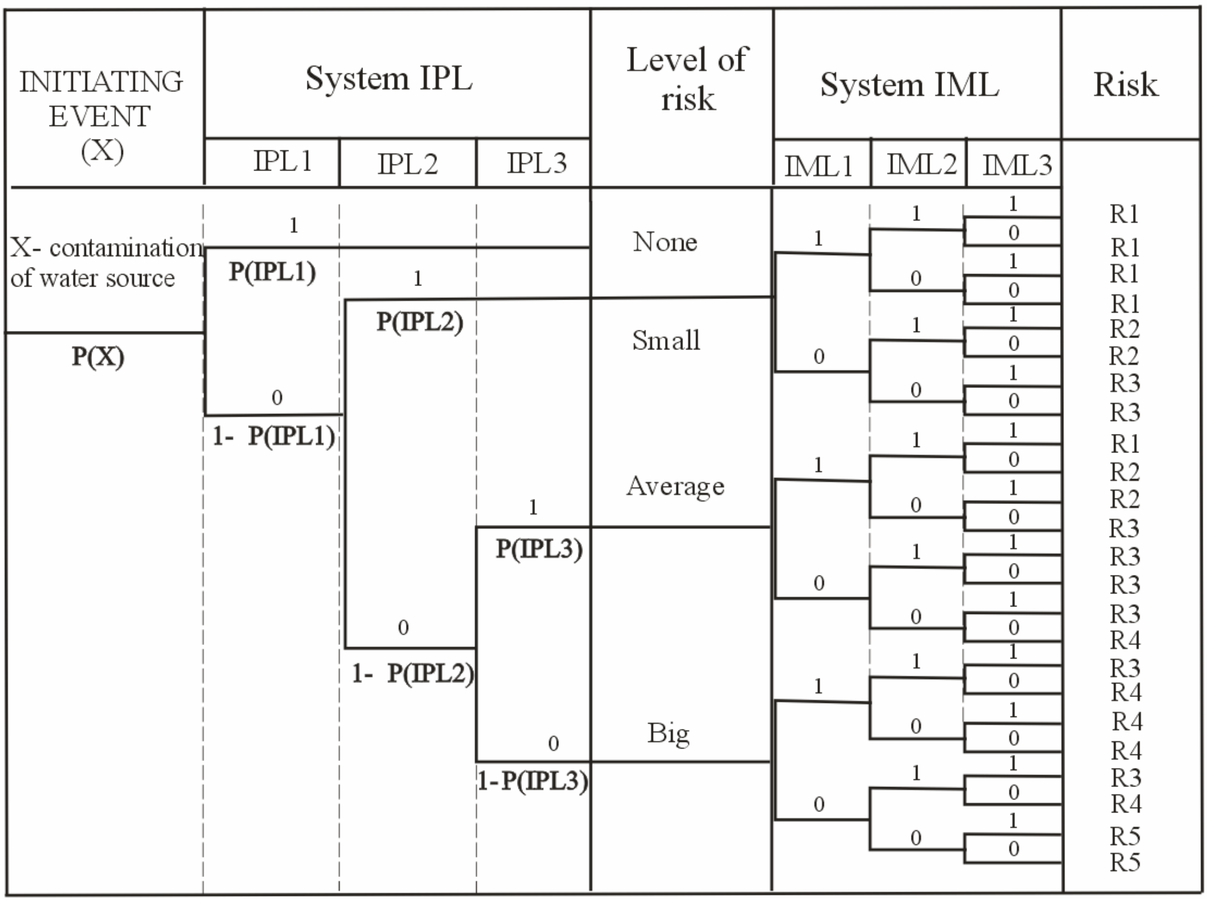

Figure 4. The event tree

Risk assessment of threat to water consumers relies on the analysis whether the individual barriers that mitigate the consequences of failure will work or not. The five-stage scale for risk assessment was adopted: *R1* - negligible risk, *R2* - tolerable risk, *R3* - controlled risk, *R4* - intolerable risk, *R5* - unacceptable risk. The assessment of the risk associated with the occurrence of the undesirable event *X* - water contamination in the source, is shown in *Figure 4*.

3. Conclusion

- The CWSS operation is inseparably connected with the possibility of failure of the subsystems during their daily operation.
- Currently, research relating to water consumers safety, which derives directly from the reliability theory, is developing.
- Risk as a measure of safety became the paradigm.
- For water supply the WHO recommends the development of the so called Water Safety Plans (WSP) based on risk analyses and assessment. The development of the WSP, although it is not currently mandatory, meets the modern standards on drinking water safety. At the same time there are still such threats as floods, droughts, electrical power failures, incidental pollution of water sources, and even terrorist and cyber terrorist attacks, which often cause serious CWSS subsystem operational disruptions and thus contribute to the loss of water consumers safety.
- Analysis and assessment of the risk of failure in CWSS should concern mainly mentioned above events, and the principle that even the most unlikely events should be taken into account as they can lead to the disastrous consequences should be applied.
- The analysis of risk associated with the operation of the various CWSS subsystems in terms of water consumers will contribute to increase consumers safety, which should be the standard in modern water supply systems. It is also important for the implementation of the principles of sustainable development in the widely understood water management.
- The used methods of risk analysis and assessment are mostly based on operational data and should take into account the analysis of the so called safety related systems that are based on the systems of barriers and systems mitigating the consequences of already existing threats.

- The event scenario analysis including system safety analysis can be performed using the known event tree method.
- The universality of the presented method and the possibility to use it in practice for a variety of CWSS characterized by their local specificity, should be emphasized.

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