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THE EVENT TREE USING IN IDENTIFICATION OF THMS' FORMATION IN WATER SUPPLY SYSTEM

IDENTYFIKACJA POWSTAWANIA THM-ÓW W SYSTEMIE DYSTRYBUCJI WODY ZA POMOCĄ DRZEWA ZDARZEŃ

W artykule przedstawiona została procedura aplikacji drzewa zdarzeń w ocenie prawdopodobieństwa występowania THM-ów w wodzie do picia. Autorzy opisali główne czynniki determinujące obecność THM-ów w systemie zaopatrzenia w wodę. Celem artykułu jest aplikacja techniki drzewa zdarzeń w zarządzaniu infrastrukturą wodociągową. Technika ta jest graficzną prezentacją wszystkich możliwych stanów systemu odpowiadających zdarzeniu inicjującemu. Technika drzewa zdarzeń oparta jest na identyfikacji barier bezpieczeństwa występujących w systemie zaopatrzenia w wodę. Wytypowane bariery mają spełniać rolę ochronną oraz monitorować i zapobiegać przedostawaniu się i transportowaniu THM-ów w systemie zaopatrzenia w wodę. Dodatkowo technika ta pozwala na wyznaczenie prawdopodobieństwa wykrycia THM-ów w wodzie do picia. Opisana technika może być użyteczna w opracowywaniu Planu Bezpieczeństwa Wodnego (Water Safety Plan).

1. Occurrences of THMs in water distribution systems

Disinfection is the last step in the water treatment plant for the protection of public health. One of the most commonly used water disinfectant is chlorine. Its commonness is the result of many factors: its low cost, convenience of application and effectiveness for killing most microorganisms. Unfortunately, natural organic matter (NOM) in water reacts with chlorine to form chlorination by-products (CBPs). The process of CBPs formation depends on water pH, contact time, residual chlorine, seasonal fluctuation, concentration of NOM, and concentration of bromide [1-7].

In 1974 Rook discovered trihalomethanes (THMs) [1]. THMs constitute the major category of CBPs [1]. Chloroform ($CHCl_3$), bromoform ($CHBr_3$). bromodichloromethane ($CHCl_2Br$) and dibromochloromethane ($CHClBr_2$) are the four compounds belonging to the group of THMs. The presence of THMs in chlorinated drinking water and they lifetime exposure on human has raised a great concern due to its carcinogenicity and recognition as risk to human health [1-4, 8-9, 33]. Several epidemiologic studies have suggested a link between THMs exposure and risk of bladder, colon, and rectum cancers [2,10] Exposure to THMs is also found to be associated with adverse reproductive outcomes [11]. The non-cancer effects of THMs are jaundice, neurobehavioral effects, subjective central nervous system effect and enlarged livers but these effects are very unlikely [12]. Due to THMs hazards to human health, USEPA has established the maximum contaminant level for total trihalomethanes (TTHMs), describes as the sum of the mass concentrations of chloroform, bromodichloromethane, dibromochloromethane and bromoform, below 80 μg /L in drinking water[13]. THMs can be taken up during drinking, showering, bathing, and swimming through three routes ingestion, contact with skin and inhalation[14].

The implementation of highly effective water treatment technology does not protect directly to the minimalization of risk of THMs concentration in tap water during water transportation in network. First of all, the presence of THMs precursors in raw water, the water temperature and pH, a kind of disinfectant may be significant to the THMs formation potential in water supply system [1-7]. The small flow rate of water is the consequence of reducing water demand and hence long time of water transportation in water supply system. Also water flow direction chganges in the network cause the deposition of mineral and organic (biofilm) matter on pipes surface [15-17]. Such conditions of water supply network management and the presence of chlorine in water may increase the risk of THMs formation in drinking water.

The safety of water infrastructure should be a priority for water supply system management. To ensure water supply system safety, water companies have to take action to optimize the process of providing required water quality during the purification of water and its transport to customers. Despite implementation of highly effective technology and other economically reasonable preventive measures, there is not possible fully protect the water supplied to consumers from the ability to change its quality in tap water. A particularly important issue is the process of formation of THMs in water distribution system. For this reason, it is very important to imply efficient method for estimation the risk of THMs occurrence in drinking water. One of this techniques, described in this paper, is an event tree method.

1.1. Factor of THMs formation in water distribution systems

The THMs concentration and speciation can be affected by many water quality parameters and operating conditions, including NOM concentration, chlorine residual, reaction time, pH, temperature and bromine concentration.

The first factor in the formation of disinfection by-products (DBPs) is a kind of disinfectant. Though the problem of DBPs formation by disinfection was initially highlighted by the discovery of THMs, subsequent studies revealed that the reaction of chlorine with traces of organic matters present in the raw water produced scores of other products also such as haloacids, haloacetonitriles, haloacetic acids and numerous other organic, inorganic and organohalogenic compounds [17].Table 1 lists the types of DBPs depending on the used disinfectant [19-20].

The process of THMs formation in water supply system requires the presence of THMs precursors (naturally present organic matter compounds, such as humic acids, fulvine acids, carboxylic acid) and chlorine in the water. Chlorine dosage is the key factor for THMs formation. Increasing chlorine dose increases the formation of THMs in treated water [32].

The speed of THMs formation process depends on raw water pH, raw water temperature, contamination of the bromine compounds in raw water and transportation/stagnation time in water distribution system.

Tab. 1 Types of DBPs depending on the used disinfectant [19-20]

Disinfectant	**Disinfection by-products**		
	Organohalogenic compounds	**Organic compounds**	**Inorganic compounds**
Chlorine Cl_2/ podhlorite acid HOCl	Trihalomethanes, halogen acetic acids, hydratem chlorine, chloropicrin, halo-acetonitryle, chlorphenoles, N-chloramines, halofura-nose	chlorane	Aldehydes, carboxylic acids, benzene
Chlorine dioxide ClO_2	-	Chlorite, chlorane	unknown
Chloramines	halo-acetonitryle, cyanogen chloride, organic chlora-mines, hydratem chlorine, haloketones	nitrite, nitrate, chlorane, hydrazine	aldehydes, ketones
Ozone O_3	Bromoform, acetid mono-bromine acid, acetid dibromine ac-id,cyanobromine	Chlorane, iodate, bromate, dihydrogen dioxide, hypobrom-ous acid, epoxide acid	aldehydes, ketones, keto acids, carboxylic acids

A number of studies have investigated THMs increase in the high pH value water. Generally, when pH values are high, more hypochlorite ions are formed, causing the effectively of chlorine disinfection to decrease. At higher pH values, more THM is formed, whereas more HAA is formed when pH values are lower. At high pH values HAN and HK are decomposed by hydrolysis, because of an increase in hydrolysis reactions at higher pH values [32].

Higher temperature also speeds oxidation of organic compounds in the THMs formation reaction rate. Research [3, 21-23] has demonstrated that THMs concentrations can increase significantly between water distribution system and the consumer's tap due to stagnation in warm water pipes. As a result, use of supply water (consumption and/or showering purposes) after a long period of stagnation warm water in the pipes and/or heating in the hot water tanks may significantly increase risks to human health [3,22-23].

The presence of bromide ions in the water increases the speed of THMs formation reaction rate even if the concentrations of dissolved organic carbon is really low. High bromide content in raw water and possibility of carry over of bromine and brominated THMs into the drinking water may alter both the quantity and species distribution of THMs [18].

Another determinant of THMs concentration is time of THMs precursors and chlorine contact. The stagnation of water in the pipes may allow additional reactions between the residual organics and free residual chlorine [3,22,23-24], which may increase THMs concentrations in the network. Depending on the size of the water supply systems, water may stay in the pipes for a considerable amount of time before it reaches taps in the house [3, 22, 24-25]. This stagnation may be even longer during off-peak hours for example midnight to morning or late morning to early afternoon [22].

Due to the fact that THMs may occurred in drinking water, the level of their concentration needs to be monitored and controlled in water distribution network [3,13,19-20].

2. Event tree

An event tree technique is a quantitative and qualitative analysis. It is a graphical logic model that identifies and quantifies possible outcomes following an initiating event in the chronological order. The procedures provides systematic coverage of the time sequence of event propagation, either through a series of protective system actions, normal plant functions, operator interventions and incident consequences. Depending on whether the security barrier does the job or not, each level of the event tree consider two logical states: success (yes) and failures (no) [26-29]. General scheme of the event tree is shown in fig. 1 [26,28].

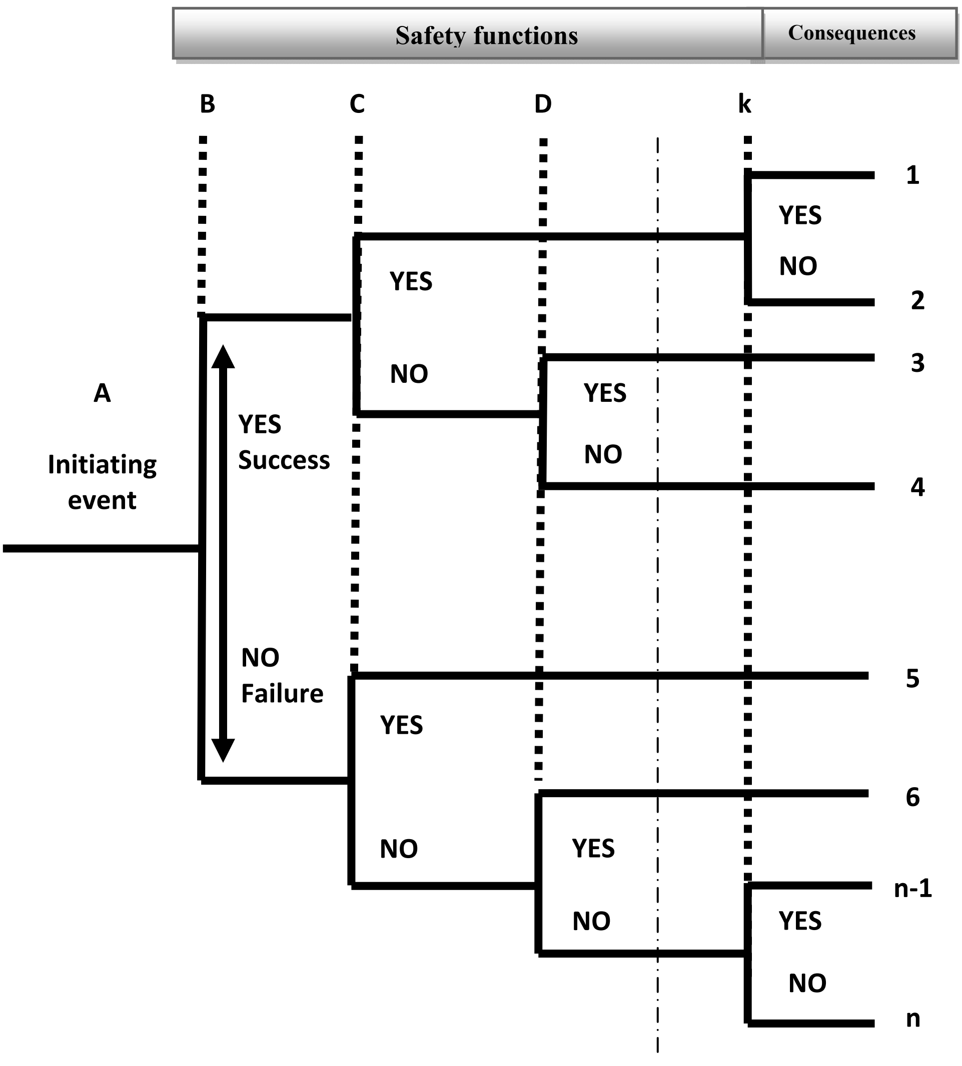


Fig. 1 General scheme of an event tree[26,28]

Construction of the event tree can be very complex. The analysis of system reliability by event tree starts from the initial event. Then analyze describes possible consequences of this event by building multiple paths (branches) trees until the final consequences. Individual events describe the behavior of the subsequent security thresholds, taking into account their correct or incorrect operation. Starting with the top event, the tree is developed until the required level of detail is reached.

When each path indicates a probability of the end result occurrence is a list of possible analysis of the consequences, along with associated probabilities. The probability of the each branch was described according to formula 1 [26].

$$P(AB..k) = \prod_{j=1}^{S} X_j^{(i)} \tag{1}$$

where:

k- number of elements (barriers),

j-an event in the event tree,

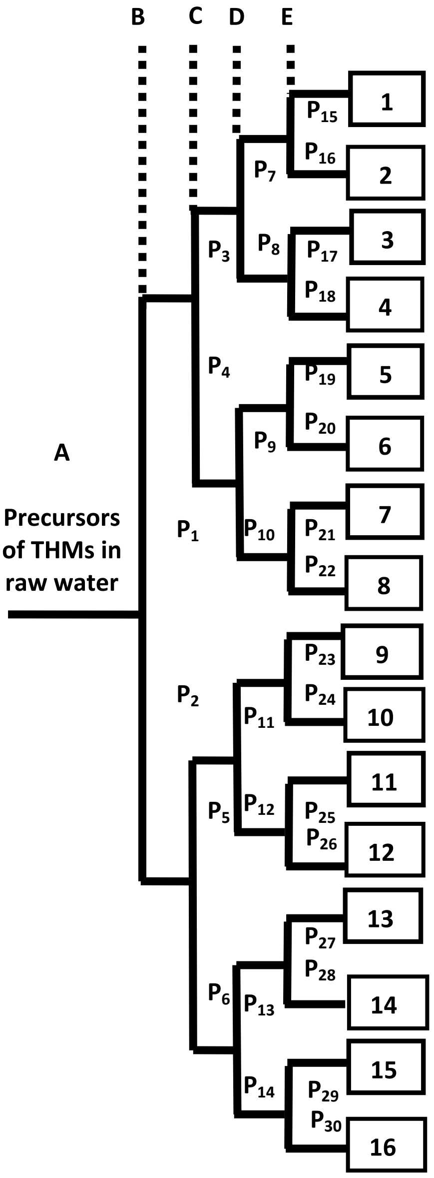
$X_j^{(i)}$- Boolean variable for " j" event in "i" branch of the event tree.

The main advantage of the event tree is that it presents the outcomes flowing from an initiating event in a systematic, logical and self documenting manner. Also, the format is compact and the logical and arithmetic calculations are simple. The event tree can be applied to either pre-incident or post-incident applications. In the case of pre-incident application the aim is to examine the systems in place that would prevent incident precursors from developing into incidents. Pre-incidents event trees are valuable in highlighting the value and/or weakness of protective systems. For post-incident applications the aim is to identify the range and likelihood of potential outcomes. Post-incident event trees highlights the range of outcomes that are possible from a given incident [27-28].

The event tree analysis is a risk estimation tool with the ability to model interactions (based on the occurrence or non-occurrence of other events) between events in water infrastructure. An important aspect when conducting risk analyses of water supply systems is to consider the entire system, from source of water to consumer's tap [20,30]. This means that the raw water and its treatment system as well as the distribution network all the way to the consumers' taps should be taken into consideration.

3. The event tree using in identification of THMs formation in water supply system

The event tree is constructed for initial event-precursors of THMs occurrence in raw water. For this initial event the water supply system in city X has particular safety functions: raw water quality monitoring (B), high efficiency of water treatment processes (C), treated water monitoring (D), service reservoir/ alternative drinking water sources (E), water quality monitoring in distribution system (F), portable flushing out station (G), individual water treatment system (H). For the identified barriers event headings are indicated at the top of the event tree diagram. If the barrier exists it is named as a "success" or "yes" branch upwards. If the barrier does not exist it is named as a "failure" or "no" branch downwards. Figures 2, 3, 4, 5, 6 show the branches in which THMs occurrence in tap water is the most possible.



B- Raw water quality monitoring

C-High efficiency of water treatment processes

D- treated water monitoring

E-Service reservoir/ alternative drinking water source

F-water quality monitoring in distribution system

G-Portable flushing out station

H-Individual water treatment system

Fig.2 event tree for occurrence of THMs precursors in raw water

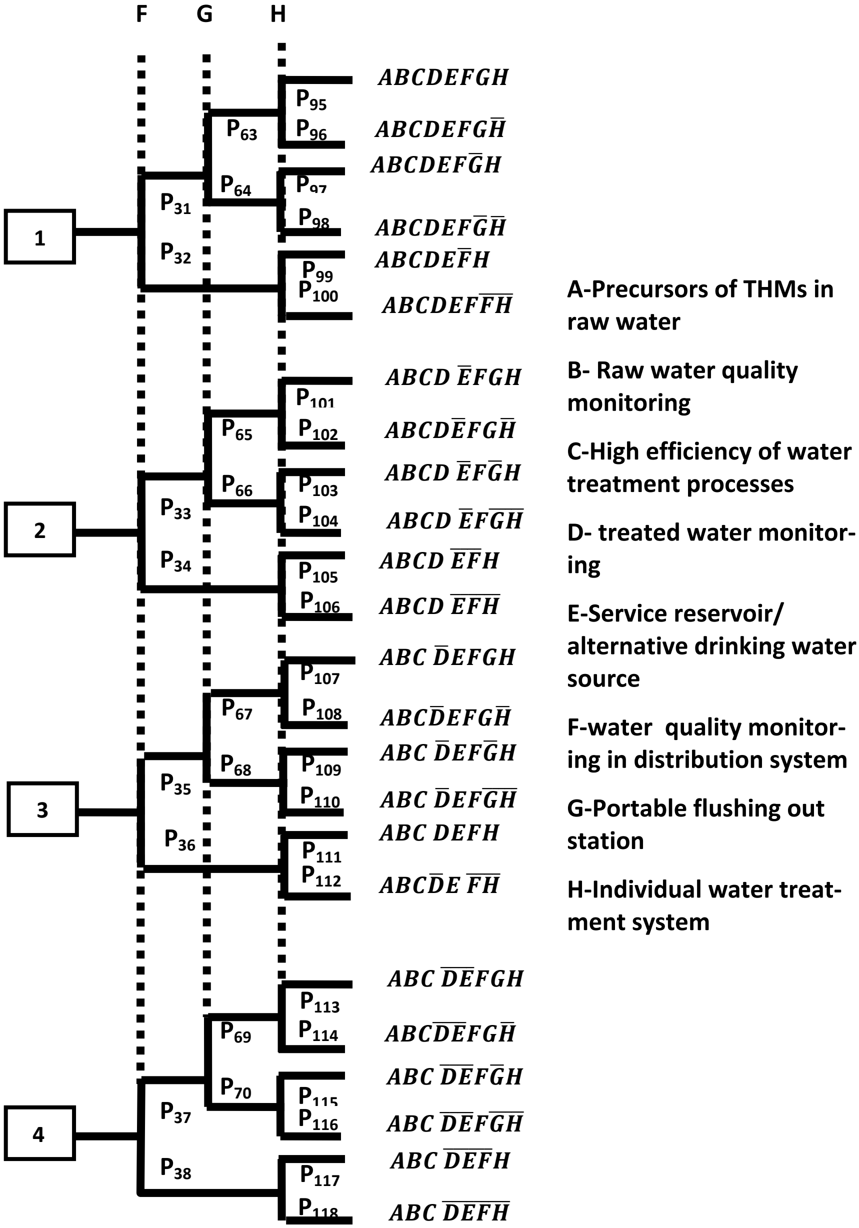


Fig. 3 Event tree for occurrence of THMs precursors in raw water

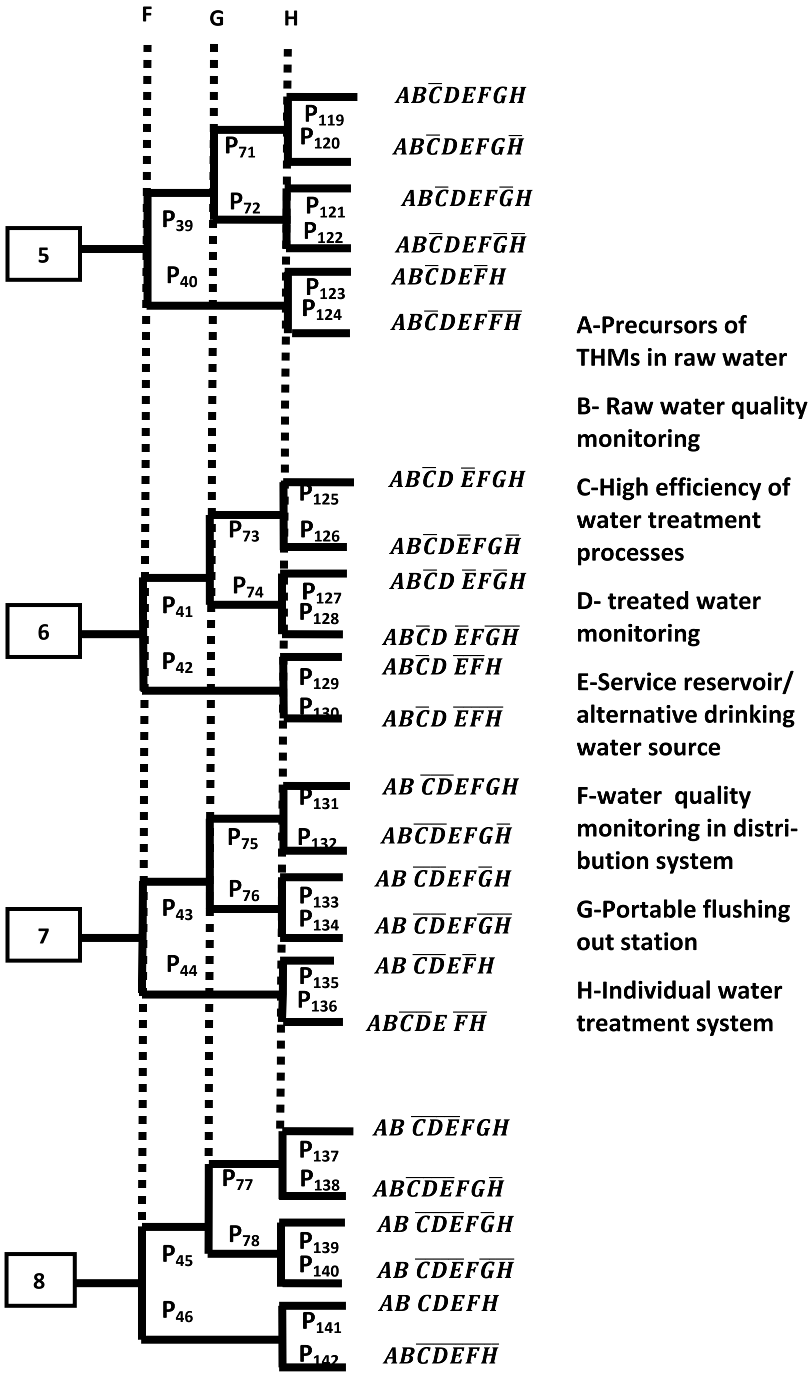


Fig. 4 Event tree for occurrence of THMs precursors in raw water

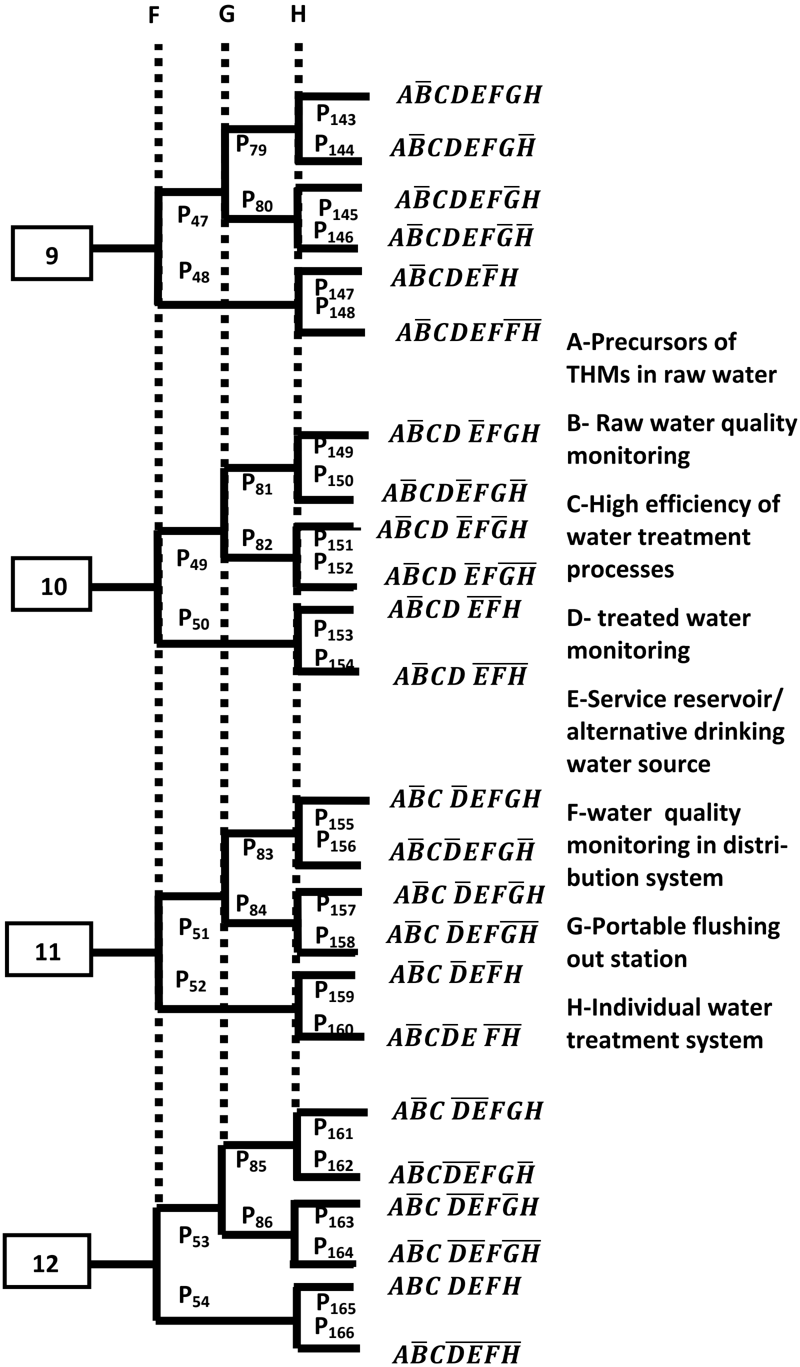


Fig. 5 Event tree for occurrence of THMs precursors in raw water

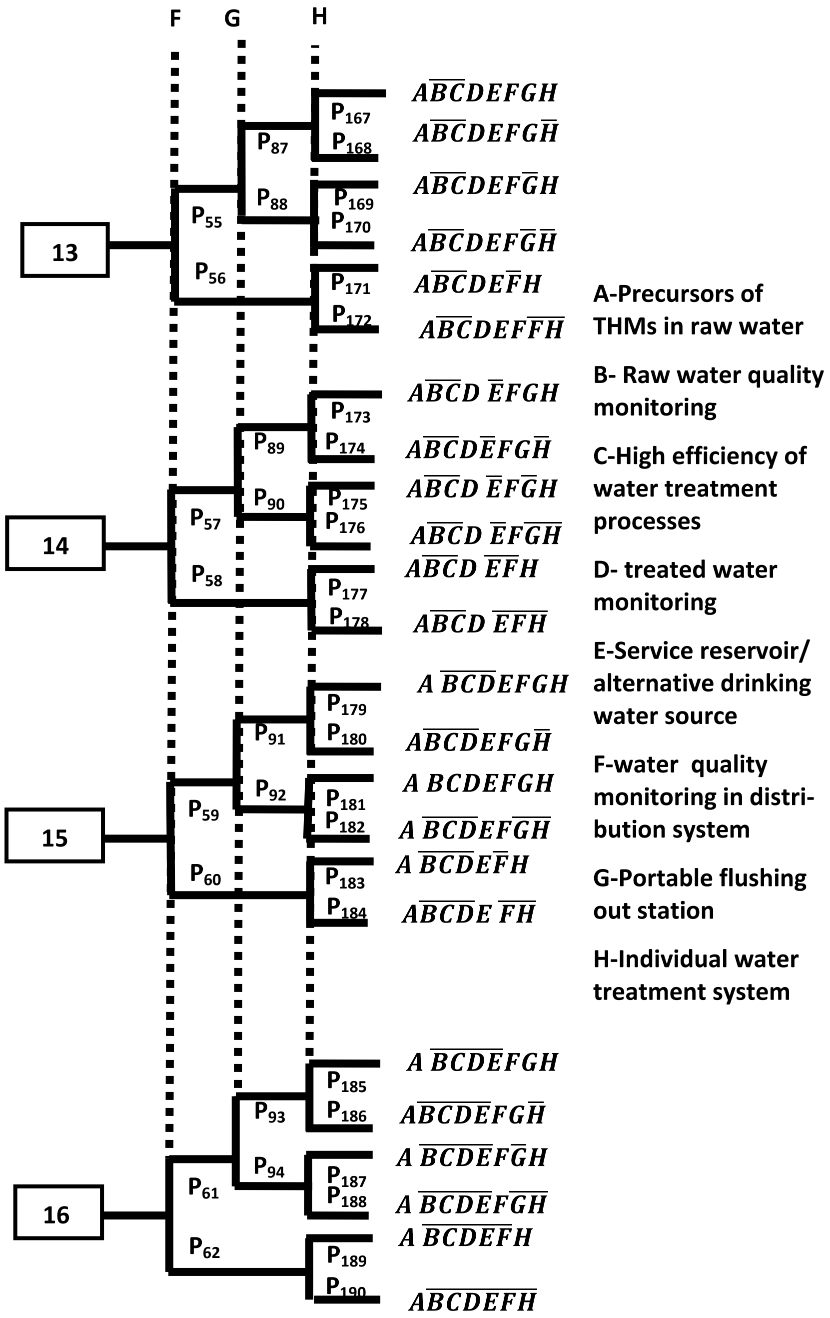


Fig. 6 *Event tree for occurrence of THMs precursors in raw water*

The event tree consider a precursors of THM's occurrence in raw water and the range of events that might follow. The event tree summarizes the range of outcomes that could result from the initial event. The event sequences in which only one or two safety functions do not exist indicate the low probability of THMs occurrence in tap water. In the sequences of events where more safety functions do not appear the probability of THMs occurrence in tap water might be very high. When the water supply system do not have any of the listed safety functions the probability of THMs occurrence in tap water is almost certain. Estimation of outcome probabilities is calculated by multiplying the probability of individual event sequence conducted from the initiating event. The probability for the twenty randomly chosen event sequences are showed in table 2.

Tab. 2 Examples of probability of the outcomes flowing from THMs occurrence in raw water

Event	Probability
$ABCDEFGH$	$P(ABCDEFGH)=P_1 \cdot P_3 \cdot P_7 \cdot P_{15} \cdot P_{31} \cdot P_{63} \cdot P_{95}$
$ABCDEFG\bar{H}$	$P(ABCDEFG\bar{H})=P_1 \cdot P_3 \cdot P_7 \cdot P_{15} \cdot P_{31} \cdot P_{63} \cdot P_{96}$
$ABC\,\bar{D}EF\bar{G}H$	$P(ABC\,\bar{D}EF\bar{G}H)=P_1 \cdot P_3 \cdot P_8 \cdot P_{17} \cdot P_{35} \cdot P_{68} \cdot P_{109}$
$AB\bar{C}DEFGH$	$P(AB\bar{C}DEFGH)=P_1 \cdot P_4 \cdot P_9 \cdot P_{19} \cdot P_{39} \cdot P_{71} \cdot P_{119}$
$AB\bar{C}DEFG\bar{H}$	$P(AB\bar{C}DEFG\bar{H})=P_1 \cdot P_4 \cdot P_9 \cdot P_{19} \cdot P_{39} \cdot P_{71} \cdot P_{120}$
$A\bar{B}CDEF\bar{G}\bar{H}$	$P(A\bar{B}CDEF\bar{G}\bar{H})=P_2 \cdot P_5 \cdot P_{11} \cdot P_{23} \cdot P_{47} \cdot P_{80} \cdot P_{146}$
$A\bar{B}CDE\bar{F}H$	$P(A\bar{B}CDE\bar{F}H)=P_2 \cdot P_5 \cdot P_{11} \cdot P_{23} \cdot P_{48} \cdot P_{147}$
$A\bar{B}C\bar{D}E\,\overline{FH}$	$P(A\bar{B}C\bar{D}E\,\overline{FH})=P_2 \cdot P_5 \cdot P_{12} \cdot P_{25} \cdot P_{52} \cdot P_{160}$
$A\bar{B}C\,\overline{DE}FGH$	$P(A\bar{B}C\,\overline{DE}FGH)=P_2 \cdot P_5 \cdot P_{12} \cdot P_{26} \cdot P_{53} \cdot P_{85} \cdot P_{161}$
$A\bar{B}C\overline{DE}FG\bar{H}$	$P(A\bar{B}C\overline{DE}FG\bar{H})=P_2 \cdot P_5 \cdot P_{12} \cdot P_{26} \cdot P_{53} \cdot P_{85} \cdot P_{162}$
$A\bar{B}C\,\overline{DE}F\bar{G}H$	$P(A\bar{B}C\,\overline{DE}F\bar{G}H)=P_2 \cdot P_5 \cdot P_{12} \cdot P_{26} \cdot P_{53} \cdot P_{86} \cdot P_{163}$
$A\bar{B}C\,\overline{DE}F\overline{GH}$	$P(A\bar{B}C\,\overline{DE}F\overline{GH})=P_2 \cdot P_5 \cdot P_{12} \cdot P_{26} \cdot P_{53} \cdot P_{86} \cdot P_{164}$
$A\bar{B}C\,\overline{DEF}H$	$P(A\bar{B}C\,\overline{DEF}H)=P_2 \cdot P_5 \cdot P_{12} \cdot P_{26} \cdot P_{54} \cdot P_{165}$
$A\overline{BC}D\,\bar{E}FGH$	$P(A\overline{BC}D\,\bar{E}FGH)=P_2 \cdot P_6 \cdot P_{13} \cdot P_{28} \cdot P_{57} \cdot P_{89} \cdot P_{173}$
$A\overline{BC}D\bar{E}FG\bar{H}$	$P(A\overline{BC}D\bar{E}FG\bar{H})=P_2 \cdot P_6 \cdot P_{13} \cdot P_{28} \cdot P_{57} \cdot P_{89} \cdot P_{174}$
$A\overline{BC}D\,\bar{E}F\bar{G}H$	$P(A\overline{BC}D\,\bar{E}F\bar{G}H)=P_2 \cdot P_6 \cdot P_{13} \cdot P_{28} \cdot P_{57} \cdot P_{90} \cdot P_{175}$
$A\overline{BC}D\,\bar{E}F\overline{GH}$	$P(A\overline{BC}D\,\bar{E}F\overline{GH})=P_2 \cdot P_6 \cdot P_{13} \cdot P_{28} \cdot P_{57} \cdot P_{90} \cdot P_{176}$
$A\,\overline{BCD}EF\overline{GH}$	$P(A\,\overline{BCD}EF\overline{GH})=P_2 \cdot P_6 \cdot P_{14} \cdot P_{29} \cdot P_{59} \cdot P_{92} \cdot P_{182}$
$A\,\overline{BCDEF}H$	$P(A\,\overline{BCDEF}H)=P_2 \cdot P_6 \cdot P_{14} \cdot P_{29} \cdot P_{62} \cdot P_{189}$
$A\overline{BCDEFH}$	$P(A\overline{BCDEFH})=P_2 \cdot P_6 \cdot P_{14} \cdot P_{29} \cdot P_{62} \cdot P_{190}$

For the numerical value of the probability the braches could be classified in one of the three risk category for THMs occurrence in tap water (table 3).

Tab. 3 Risk categories for THMs occurrence in tap water [31]

Probability	Risk category for THMs occurrence in tap water
P≤0,04	Tolerable risk
0,04<P≤0,1	Controlled risk
P>0,1	Unacceptable risk

For the tolerable risk to cause precursors of THMs occurrence in raw water, many safety functions need to occur simultaneously: water quality monitoring, high efficiency water treatment technology, alternative sources of water or individual water treatment process. In case of controlled risk an operator of water supply system need to take action for improving water quality for example flushing out pipes, changes in water treatment process. For the unacceptable risk to cause precursors of THMs occurrence in raw water, the water quality is unacceptable and an operator of water distribution system have to decide to stop the delivery. When the water quality is unacceptable although the quality deviation is not detected and hence no action is possible.

4. Conclusion

The safety of water supply system should be a major aim for water supply system management. It is important to ensure water quality in each steps of water distribution: during the purification of water and its transport to customers. Safety of water supply system takes into consideration the THMs concentration in water distribution system. The most significant point in THMs contamination controlling in distribution system is monitoring. Properly located monitoring points in the water distribution system (raw water quality monitoring, treated water monitoring, water quality monitoring in distribution system) can greatly reduce the risk of THMs occurrence in the water supply system.

The event tree technique using for water supply system allows to minimizing the impact of catastrophic events. The event tree analysis, applied for identification of water supply system safety functions, allows to identify steps that should be taken to reduce the risk of THMs occurrence in tap water.

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