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A Safety Assessment for Consumers of Water Using Logical Trees

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Abstract: The lack of biochemical stability in drinking water increases the secondary contamination risk in water supply systems and hence represents a sanitary threat to consumers. The work presented here assesses the likelihood of such risk. The assessment is based on data obtained from one of the water treatment plants. The assessment of the bio-chemical instability risk combines both approaches: fault and event trees. Additional consideration was naturally given to the events that initiated the contamination at the outlet of the water treatment plant. It is concluded that if it is to protect the water-supply infrastructure representing a kind of critical infrastructure, a water-supply company needs to put more emphasis on the distribution of stable water in terms of its properties and composition, thus having no potentially corrosive properties. The assessment underlines the importance that water supply utilities should equally consider both the supplied water sanitary quality and the water supply service continuity.

Keywords: water supply; chemical and biological stability of water indexes; safety of operation; fault tree analysis (FTA); event tree analysis (ETA); hybrid model of logical trees

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1. Introduction

The quality of a water-supply service lies in the ability of the utility to continue the water-supply service despite the occurrence of various types of adverse events. The primary entity to whom the concept of water safety applies is the consumer [1,2]. The probability measures the likelihood of the safety loss risk that an adverse event (cause) affects the health or the life of water consumers (effect) [3,4].

As a result of the development of water treatment technology, water directed to the water-supply network meets strictly-defined standards and recommendations [5,6]. Water supplied to recipients must be of proper quality at the point of entry into the supply system and at the point of delivery to consumers [7,8]. During the transport of water to the recipient, there is often a deterioration of its quality, reflecting the network structure materials, the generation and peeling off of biofilm, and the accumulation and releasing of deposits [9,10]. However, irregular water quality changes can cause physicochemical and microbiological instability of the pipeline's material characteristics [11,12]. This occurrence may release sediments, chemicals, and microorganisms that have accumulated over decades, posing health risks and, at the very least, creating aesthetic issues with the turbidity and color of tap water [13,14].

Alongside the supply network's technical condition, water's lack of physical, biological and chemical stability is considered the main reason for water quality degradation [15].

- Treated water introduces into the distribution system [16,17];
- Material charge (suspensions and particles);
- Microbiological charge; and
- Organic and inorganic nutrients.

Secondary water pollution entailing changed parameters, may compromise safety and pose a threat to water consumers. The risk to consumers lies in possible water supply disruption or in supplying water with degraded quality. This can result in damage to health, even threaten people's lives, or cause losses in the case of business customers [18].

Risk analysis should be based on the system's historical and operational feedback, robust analytical methods, and field experience [19–21]. Ways of limiting the exposure risk of consumers would be as follows [1,2]:

- Threat removal = elimination;
- Consumer evacuation from the danger zone = evacuation;
- Danger confinement barriers = insulation;
- A danger barrier = insulation;
- Individual consumer protection (e.g., Through the use of water in containers).

The multi-barrier system effectively reduces consumers' exposure risk to contaminated water [1]. This system aims to ensure a high level of security in the drinking water supply. It thus assumes that specific countermeasures will be developed for each identified type of threat as the so-called "barrier." Where these come together to form a comprehensive, cohesive system to combat threats of all kinds, this is termed "multi-barrier".

2. Adopted Methodology

Proposed here is the use of a hybrid method to assess the safety of water consumers using basic logical trees.

Fault Tree Analysis (FTA) offers a graphic depiction of the link between events that have an impact on the likelihood of a particular "top event." A Fault Tree (FT) uses functors (logic gates). Figure 1 shows the basic symbols used to create a fault tree after [16,22,23].

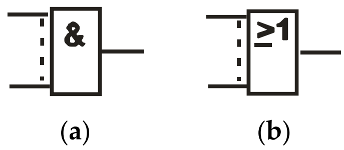

Figure 1. Basic symbols used to create a fault tree: (**a**) AND gate, (**b**) OR gate [16,22,23].

The gates represent two logical operators: "OR" and "AND." The OR gate indicates that the top event happens if at least one of the elementary events occurs. In gate AND, the top event occurs if all elementary events occur.

The following are the calculation formulas for gates' output events' probability [16,23,24] under the condition that all implied elementary events are independent:

1. gate AND:

$$P(X \times Y \times N) = P(X) \times P(Y) \times P(N), \quad (1)$$

where:

- $(X \times Y \times N)$ is the gate AND output event,
- X, Y, . . . , N are input events,
- $P(X \times Y \times N)$ is the probability of the gate AND output event,
- P(X), P(Y), . . . , P(N) are the probabilities of input events into logic gates X, Y, . . . , N.

2. gate OR:

$$P(X + Y) = P(X) + P(Y) - P(X) \times P(Y), \quad (2)$$

$$P(X + Y + N) = P(X) + P(Y) + P(N) - P(X) \times P(Y) - P(X) \times P(Z) - P(N) \times P(Y) + P(X) \times P(Y) \times P(N), \quad (3)$$

where:

- (X + Y) is the gate OR output event,
- P(X + Y + N) is the probability of the gate OR output event.

Event Tree Analysis (ETA) relates to the development possibilities of an initiating event. Security barriers are then identified to limit the negative effects of such an event. Event sequence development is considered sequentially, with account taken of security barriers. At each level of the event tree, the two logical states considered are a success (yes) and failure (no), depending on whether a given safety barrier does its job or not. It is possible for both qualitative and quantitative event trees to be analyzed. In the latter case, a branch describing success has a probability P_i assigned to it, while the branch identified with failure is $1 - P_i$ [23]. Following a top event(s), there may be the generation of undesirable events whose existence depends largely on the functioning and mobility of subsequent security and safety subsystems and external conditions (the surroundings). The effectiveness of the countermeasures is then expressed in terms of the consumers' protection success or failure in case of exposure to contaminated water use [24,25].

A comprehensive analysis was performed using the event-tree and fault-tree methods.

3. Studied Case Characterization

The selected water supply system is in a city supplied by a bank-edge water intake of 90,000 m^3/d capacity. Water is treated at two independent water-treatment plants, using identical technology, with preozonization, coagulation provided by a synthetic flocculant (when temperatures are low), and horizontal settling tank sedimentation. Filtration is on fast filters, which are sand filters in the case of the first water treatment plant. The second water treatment plant uses anthracite-sand filters, with indirect ozonation and BAF carbon filters. The intermediate ozone chambers are completely separated. Water after ozonation goes to four chambers of carbon filters and from there to its own clean-water reservoirs.

Treated water meets the quality requirements set for water intended for human consumption.

The average daily production of treated water is about 37,000 m^3/d, fully satisfying the needs of customers where water is concerned.

The 900 km long water delivery network is made up of a 49 km main network, a 529 km distribution network, and a 322 km domestic connection network. Cast-iron and steel pipes make up the main network, while cast-iron, steel, PE, and PVC pipes make up the distribution network. Cast iron, PE, and PVC are the principal materials used to make household connections. Four mains that carry water purified at the second-degree pumping station make up the examined water supply network.

4. Application Example

Figure 2 presents such a hybrid method prepared for an event scenario according to the logic-gate symbols from Figure 1, leading to a change in water quality in a supply network due to its loss of chemical or biological stability [26,27].

The meanings of the symbols in Figure 2 are as follows:

- I is a protection barrier related to the identification of contamination through the monitoring of water quality in the supply network,
- II is a protection barrier related to a warning system targeted at the recipients of water,
- III is a protection barrier related to the methods of prevention via a crisis water-supply system.

A comprehensive analysis was performed where the event-tree and fault-tree methods were combined through the hybrid model.

The hybrid model's specific designations, based on [16,28,29] and featured in Figure 2, are presented in Tables 1 and 2 below.

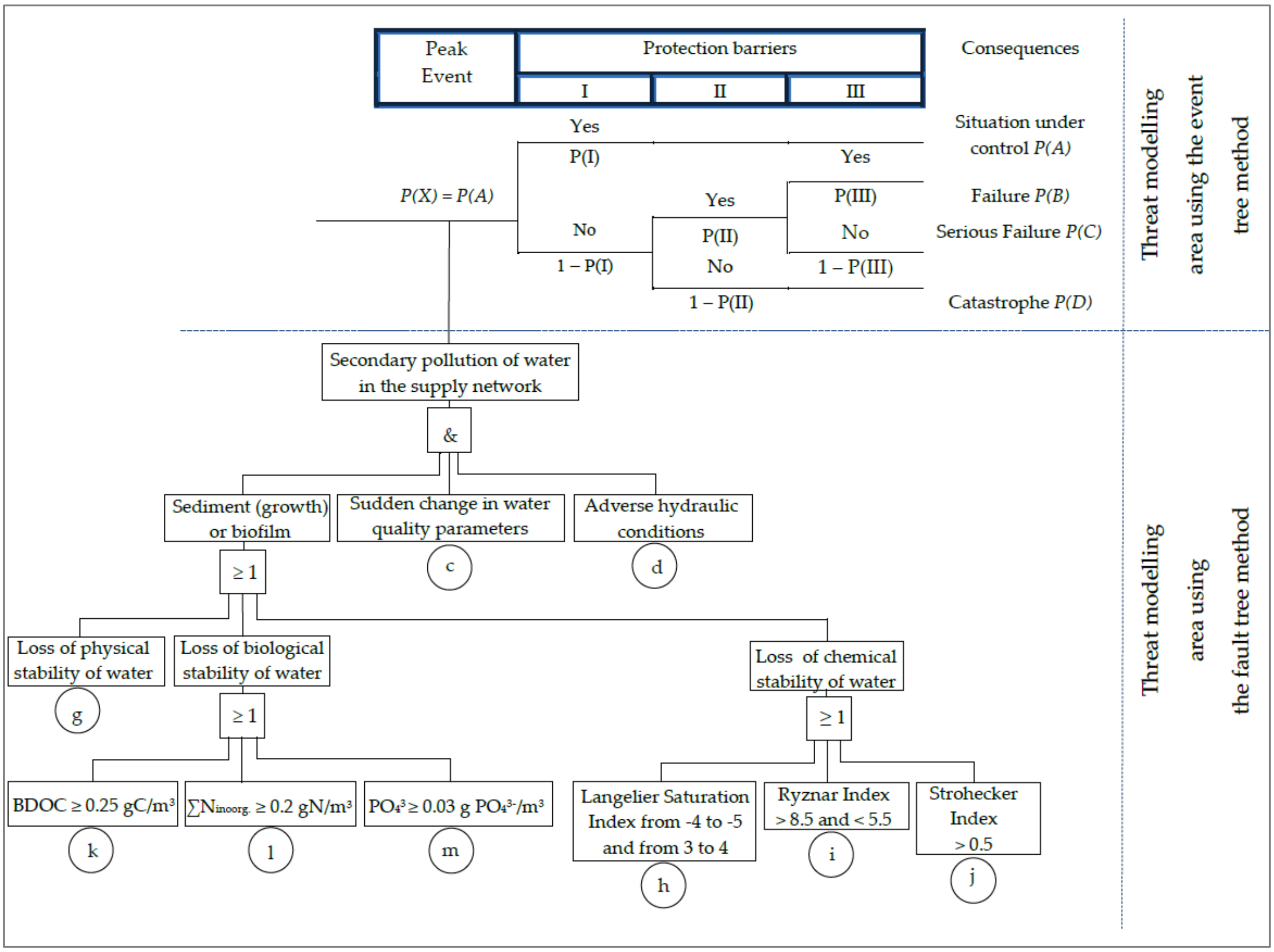

Figure 2. Hybrid Model of logical trees after a peak event related to the secondary water pollution in the water supply system.

Table 1. Specific designations of the fault tree.

No.	Designation	Description
1.	a	Event related to the occurrence of secondary pollution of water in the supply network
2.	b	Event related to the occurrence of sediment (growth) or biofilm
3.	c	Event related to the occurrence of adverse hydraulic conditions
4.	d	Event related to an unexpected change in water quality parameters
5.	e	Event related to a lack of water chemical stability
6.	f	Event related to a lack of water biological stability
7.	g	Event related to a loss of physical stability of water resulting in the limit value for water turbidity being exceeded ($\geq$0.8 NTU)
8.	h	Event related to the emergence of a water-quality situation with a Langelier Saturation Index value from -4 to -5 and from 3 to 4
9.	i	Event related to a lack of water chemical stability of water with a Ryznar Index value of >8.5 and <5.5
10.	j	Event related to a loss of chemical stability of water with a Strohecker Index value of more than 0.5
11.	k	Event related to a lack of water biological stability with a biodegradable dissolved organic carbon (BDOC) water-quality value of $\geq$0.25 gC/m^3
12.	l	Event related to a lack of water biological stability with a $\sum N_{inorganic}$ value of $\geq$ 0.2 gN/m^3
13.	m	Event related to a lack of water biological stability with a PO_4^{3-} value more than 0.03 g PO_4^{3-}/m^3

Table 2. Probabilities of occurrence of specific events.

No.	Probability	Description	Value
1.	P(a)	Probability of an event related to the occurrence of secondary water pollution of water in the network	Calculated acc. to Equation (4)
2.	P(b)	Probability of an event related to the occurrence of sediment (growth) or biofilm	Calculated acc. to Equation (5)
3.	P(c)	Probability of an event related to the occurrence of adverse hydraulic conditions	0.015
4.	P(d)	Probability of an event related to a sudden change in water-quality parameters	0.0001
5.	P(e)	Probability of an event related to a loss of chemical stability of water	Calculated acc. to Equation (6)
6.	P(f)	Probability of an event related to a loss of biological stability of water	Calculated acc. to Equation (7)
7.	P(g)	Event probability related to a lack of water physical stability of water resulting in the limit value for water turbidity being exceeded ($\geq$0.8 NTU)	0.013
8.	P(h)	Probability of an event related to the emergence of a water-quality situation with a Langelier Saturation Index value from -4 to -5 and from 3 to 4	0.0001
9.	P(i)	Event probability related to a loss of chemical stability of water with a Ryznar Index value of >8.5 and <5.5	0.015
10.	P(j)	Probability of an event related to a lack of chemical stability of water with a Strohecker Index value less than 0.5	0.0002
11.	P(k)	Event probability related to a lack of biological stability of water with a biodegradable dissolved organic carbon (BDOC) water-quality value of $\geq$0.25 g/cm^3	0.583
12.	P(l)	Probability of an event related to a loss of biological stability of water with a $\sum N_{inorganic}$ value of $\geq$0.2 gN/m^3	0.159
13.	P(m)	Probability of an event related to a lack of water biological stability with a PO_4^{3-} value of $\geq$ 0.03 g PO_4^{3-}/m^3	0.01

Probability values were adopted on the basis of the analysis, expert knowledge, and data presented by Wolska in a monograph [10] detailing the percentages of raw and treated water samples, in which limit values for the food substrates adopted for the stability assessment were exceeded. For BDOC, the probability of the limit value of 0.25 gC/m^3 being exceeded is 0.583; for $\sum N_{inorganic}$, the probability of the limit value of $\leq$0.2 gN/m^3 not being exceeded is 0.159; and for PO_4^{3-}, ($\leq$0.03 gPO_4^{3-}/m^3) the corresponding value is 0.01.

Occurrence probabilities of these specific events determined on the basis of risk criteria [16,28,29] and Figure 2 are as presented in Table 2.

The probability of a peak event related to secondary pollution in the water-supply network was calculated by reference to relationships 1–3, in line with the formulae:

$$P(a) = P(b) \times P(c) \times P(d), \tag{4}$$

$$P(b) = P(e) + P(f) + P(g) - P(e) \times P(f) - P(f) \times P(g) - P(e) \times P(g) + P(e) \times P(f) \times P(g), \tag{5}$$

$$P(e) = P(h) + P(i) + P(j) - P(h) \times P(i) - P(i) \times P(j) - P(h) \times P(j) + P(h) \times P(i) \times P(j), \tag{6}$$

$$P(f) = P(k) \times P(l) \times P(m), \tag{7}$$

In an examined supply network, secondary water pollution has a probability of 4.3496×10^{-8}.

The operational information used to support these issues relates to the operation of a municipal water company-managed supply system in the real world. Its managers' and services' information as well as technical documentation, were used to assess the individual probabilities. Above all, the research discussed here aimed to propose a mechanism for evaluating the risk of changes in water quality in a distribution subsystem.

Individual probabilities of secondary water pollution in a supply network calculated based on Equations (8)–(11) are presented in Table 3.

Table 3. Individual probabilities of secondary pollution of water in a supply network.

No.	Probability	Description	Value
1.	P(X) = P(A)	Probability related to the occurrence of water-quality parameters not in accordance with the Regulation on the quality of water intended for human consumption (Directive 1998)	4.3496×10^{-8}
2.	P(I)	Probability of failure of the protective barrier related to the identification of contamination by monitoring the quality of water in the supply network	0.002
3.	P(II)	Probability of failure of the protective barrier related to a warning system for consumers of water	0.03
4.	P(III)	Probability of failure of the protective barrier associated with methods of prevention via the crisis water-supply system	0.04

Probabilities were derived on the basis of the relationship:

- Situation under control:

$$P(A) = P(X) \cdot P(I), \tag{8}$$

- Failure:

$$P(B) = P(X) \times (1 - P(I)) \times P(II) \times P(III), \tag{9}$$

- Serious failure:

$$P(C) = P(X) \times (1 - P(I)) \times P(II) \times (1 - P(III)), \tag{10}$$

- Disaster:

$$P(D) = P(X) \times (1 - P(I)) \times (1 - P(II)). \tag{11}$$

Probability values for consequences depending on the action of protective barriers are:

- $P(A) = 8.699 \times 10^{-11}$,
- $P(B) = 5.209 \times 10^{-11}$,
- $P(C) = 1.250 \times 10^{-9}$,
- $P(D) = 4.211 \times 10^{-8}$.

In order to determine the categories relevant to acceptability, tolerance, or control of risk and enable comparisons between water distribution systems, an analysis of the kind carried out here will help set threshold values for the acceptability of probabilities. The effectiveness of assessments of specific treatment stations will be aided by a comparison between the probability value attained and the value considered acceptable.

5. Conclusions

Risk analysis relating to the potential for various unfavorable events should be added to the procedures for the proper design, construction, and operation of water delivery systems. Along with directly compromising consumer safety, these practices substantially impact the water supply's security in metropolitan agglomerations. Water entering the water supply network with better and better quality characteristics is made possible by modern treatment technology. Nevertheless, this does not ensure that water with equally good parameters will reach consumers. The main reason for that lies in the condition of networks and installations. It frequently happens that water that is of acceptable quality and meets the requirements of the relevant legislation is nevertheless aggressive and unstable, capable of causing significant financial losses. Regular variations in the water quality can cause the pipeline material to become physical-chemically and microbiologically unstable, resulting in the growth and accumulation of various materials.

In an examined supply network, the secondary water pollution probability is 4.3496×10^{-8}. In order to determine the categories relevant to acceptability, tolerance, or control of risk and enable comparisons between water distribution systems, a study of this kind will assist define threshold values for the acceptability of probabilities. The effectiveness of assessments of specific treatment stations will be aided by a comparison between the probability value attained and the value deemed acceptable.

The measure of water biological stability of water involves the achievement of criteria values for biogenic substances conditioning non-development of microorganisms so that an adequate level of safety is assured from the water source through to the recipient. Further research estimating the probability associated with the risk of instability will see determinations made in regard to both criteria for and types of corrosion that may occur depending on the quality of water and the used materials in constructing a given network. It should be noted that in each case, corrosivity criteria must be adapted to a water-distribution system's specific case.

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