# SCENARIOS OF PREVENTION AND MITIGATION OF EXOGENOUS THREAT TO WATER SUPPLY INFRASTRUCTURE

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**Abstract**

*This paper is focused on the failure of the drinking water supply systems management and protection strategies. Drinking water systems are subjected, to a greater or lesser degree, to hazards. In reality it is impossible to make every single structure perfectly immune to the failure. This paper provides a brief overview of the concept of a linguistic variable for the identification and determination of weak and critical elements of drinking water systems. Scenarios are a significant alternative for the description how the future might unfold. The key principle of water policy is the thought that we should deal with the pollution as close to its origin as possible (catchment protection).*

**Keywords**

*Critical infrastructure, disaster scenario, drinking water, exogenous threats, linguistic variable and fuzzy sets, redundancy configuration.*

The article deals with the issue of a water system failure as a result of a natural or antropogenic disaster including a terrorist attack. The aim was to indicate the importance and criticality of major elements of this system. In risk analysis we applied the theory of fuzzy sets and a linguistic variable. For subsequent practical activities of the enhancement of the security of water systems the axiomatic theory of the benefit and a multi-criteria decision making process are of an undeniable importance.

The performance was carried out with the financial project support of the MoI of the CR “Security assessment of the infrastructure elements and alternative options of the enhancement of the drinking water security in towns and villages during the rise of natural disasters and extensive industrial breakdowns” – MoI CR reg. no. VF20102014009.

## Introducing the issue

Water uptake for man represents a basic physiological need; in the CR 9.787 million inhabitants are dependent on the public water system net, i.e. 93,1 %

of total population (year 2010; source Czech Statistical Office). Drinking water production and distribution belong among the most vulnerable critical infrastructure with fatally imminent consequences. The problem is embedded in the properties of water which accepts and at the same time dissolves very well other substances. The weakness is the fact that e.g. people´s getting ill is the first mark of an enemy attack (the first signal).

An external threat to the water supply systems, i.e. a scenario of a danger[1] is dependent on the impact of a natural disaster, on an enemy or unintentional inducing of a technological breakdown, pollution with a chemical, biological or radioactive substance; damaging, destruction or sabotage of physical infrastructure and the destruction of a control computer system. A scenario (model) of a disaster is a set of isolated and interconnected impacts in space and time which induces or might induce the outbreak of events differing from the supposed state or the development of a system (entity), its integrity and function. It is a time sequence of events after the outbreak of a disaster in the area affected by the impact of a disaster.

The possibility of enhancing security/reliability[2] is elementary focused on three main scenarios, see [6], [20], i.e.

(i) through physical security – fence, cameras, guard etc.,
(ii) through control consumer nodes of residual disinfection,
(iii) through sophisticated localization “on-line” pollution monitoring stations.

The fourth scenario might be the enhancement of resilience and flexibility. A system resistant to the failures provides the protection against the failure and helps increase maximal productivity. Is it a redundant configuration[3] of critical elements, monitoring, response, and recovery.

The exceptional emphasis on the security of drinking water is exclusively documented in two relevant documents, i.e. in *Bonn charter for drinking water security* of 2004 [12] and in *Plans for water security. The management of the drinking water quality from the catchment basin to a consumer* [33]. The world database [10] offers an extensive overview of historically recorded events of water terrorism during the period from 1748 till 2006.

## Risk analysis of a water-supply system pursuant to the theory of fuzzy sets

The category of a drinking water system supply SZV implicitly covers the vague terminology of the EU where instead of drinking water they use the wording “water for human consumption”, see the Guideline 98/83/ES [30]. The structure of SZV is generally formed by a water source, collection and filter plant, accumulation, pumping, pipe net and a control center (command office, dispatch). A model virtual scheme of a combined water supply system is illustrated in fig. 1. If some elements of the system are disabled, it has a specific impact on the operability of a system as a whole. Versus real configuration of real SZV we see a different degree of criticality of individual elements from the viewpoint of their exogenous threat.

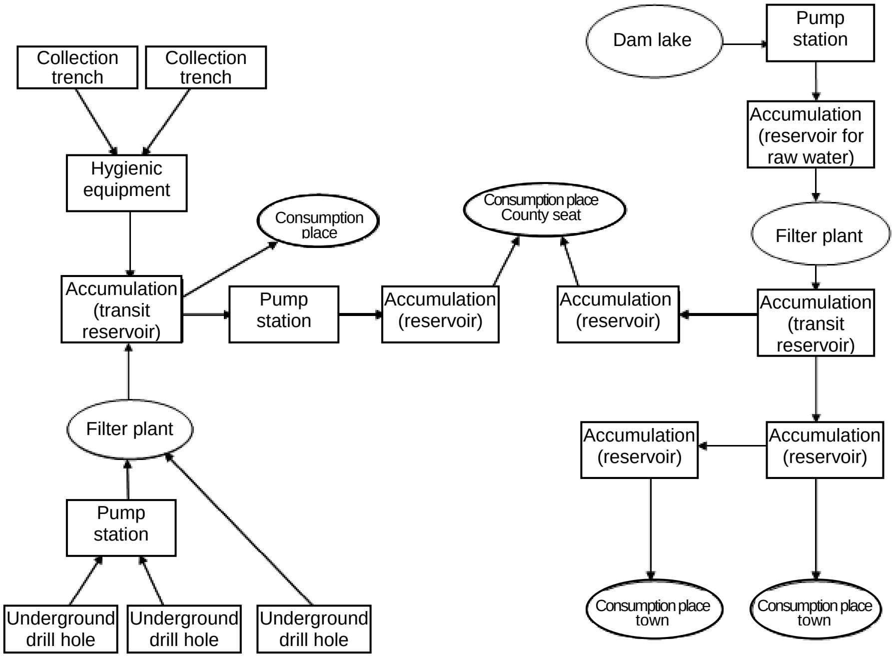


*Fig. 1*
*Model virtual scheme of a water-supply combined system; according to [27].*

Within the research project of the MoI of the CR reg. no. VF20102014009, see [27], we observed the behavior and criticality of twenty elements of a hypothetical drinking water supply system whose overview is in table 1. Theoretical starting point was a fuzzy risk analysis. We applied the theory of fuzzy sets and fuzzy logic [25]. In other words in a team expert way we assessed the importance of the malfunction (failure) of an element of a system from the aspect of reliable function of the drinking water delivery in required amount, quality and time to an end user ("on the tap") using a method of fuzzy sets and a linguistic variable. 14 researchers of a research task took part in the questionnaire. The transformation of verbal statements [VV] on auxiliary points [PB] was carried out using a code key Ecoimpact FORMULA[4] of 1994 [24].

*Table 1*
*The list of assessed elements of a hypothetical drinking water supply system according [27].*

| Id. no. | Element of a system | Id. no. | Element of a system |
|---|---|---|---|
| 01 | water collection-surface-catchment basin (to a specific consumption profile) | 11 | filter plant – control system (control center, dispatching) |
| 02 | water collection-surface-water flow | 12 | filter plant – mechanically - filtration |
| 03 | water collection-surface-reservoir | 13 | filter plant – chemical way - sedimentation |
| 04 | water collection-surface-from reservoir/dam-off-take tower | 14 | filter plant – chemical way - clarifiers |
| 05 | water collection-surface-water flow – surge construction (element) including a consumption entity | 15 | accumulation – storage reservoir - earth |
| 06 | water collection-surface-from water flow-collecting facility | 16 | accumulation – storage reservoir – tower |
| 07 | water collection-surface-catchment basin (to a specific consumption profile) | 17 | pipe/water network – supply line including fixtures (caps/slide-valves, hydrants, air-relief valves, reduction valves, sediment sludge boxes, etc.) |
| 08 | water collection-underground - collecting entity | 18 | pipe/water network – supply line |
| 09 | gas station – accumulation tank (for raw or treated water) | 19 | pipe/water network – distribution net – independent water main |
| 10 | gas station – engine room (for raw or treated water) | 20 | distribution network – water supply connections |

The objective of the investigation was to determine numeric values of a risk index $I(R\text{-}fuzzy)_i$ separately for each element of a system; the relation for the index is

$$I(R\text{-}fuzzy)_i = P_i \times D_i \quad , \qquad (1)$$

where $P_i$ . . . probability of the realization of a potential threat for assessed element of a system [%],

$D_i$ ... impact of the malfunction or failure of an assessed element of a system [PB] for $i \in$ (1 to 20).

Both magnitudes were classified according to a principle

**"the higher . . . the worse"**

A working scenario anticipated a special case for risk assessment for equivalent values of the probability of potential threats. In other words for $P_i$ ,= const., where $i = 1,2,\ldots, n$, whereas $n = 20$. reduces to

$$I(R\text{-}fuzzy)_i = D_i \,. \qquad (2)$$

For equivalent values of probability of potential threats we discovered the riskiness of individual elements of a system in three categories marked as unacceptable risk, conditionally acceptable and acceptable risk. In the category of unacceptable risk we evaluated almost all kinds of raw water collection (indexes according to a sequence 07, 01, 03, 05, 06, 04, 02, 08); and on the contrary as acceptable risk appears for pipe/water supply network - distribution network - water supply connections (index 20), complete visualization see fig. 2.

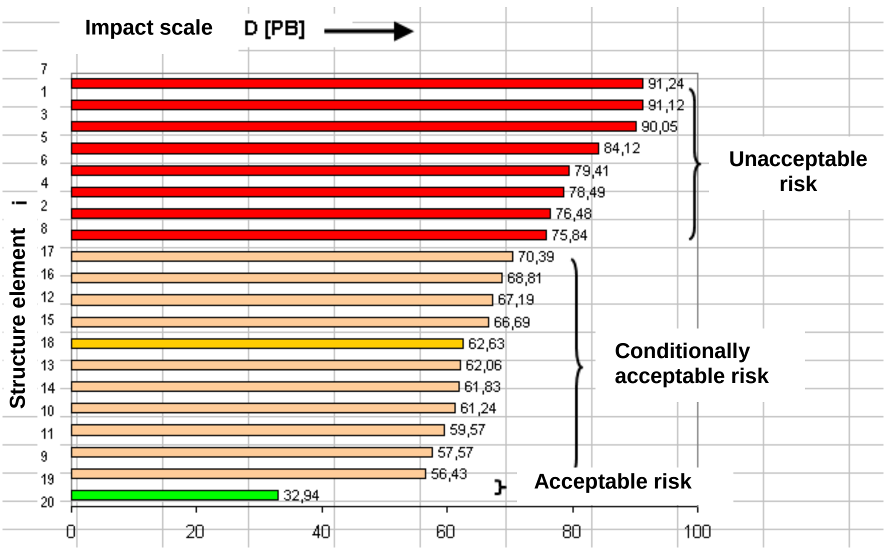


*Fig. 2*
*Hierarchy of the impact of the malfunction of elements of a system for P = const.*

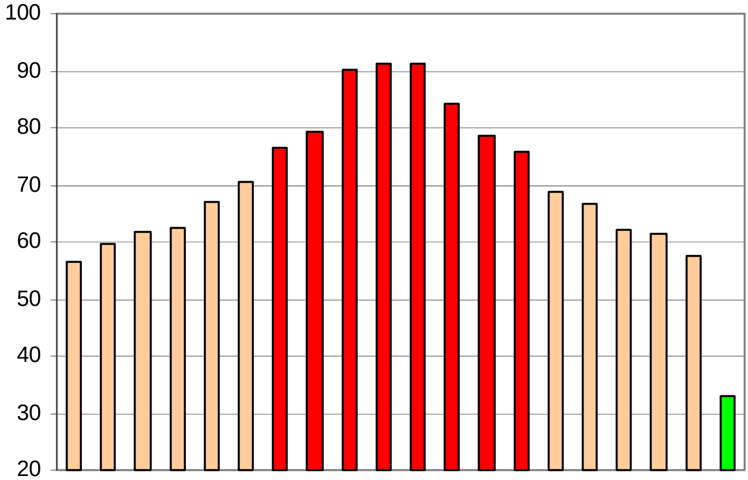


*Fig. 3*
*Test of the division of priorities of the system elements*

*Notes to fig. 3:* The diagram is created by gradual setting out the totals of advantages from the median in turns on the left and right side from the highest to the lowest value. The peaks of a column diagram marks an envelope curve for so called normal division of accidental errors (Gauss division). This way we prove the objective representativeness of the result without disturbing external (targeted) influence.

The study [27] was completed by a test of division of accidental errors (fig. 3) and a test of the concordance of experts, i.e. the analysis of the consistence of the statement of experts through the method of concordance. Control calculation of the coefficient of concordance $\Gamma$ was made according to M. Kendall [15]. From the mentioned assessment we found out a significant fact that the concordance of the statement of experts is statistically important due to the value $\Gamma$ = 0,562 and [( $\chi^2$ = 149,5 ) >>> ( $\chi_p^2$ = 10,12 )] with the number of the degrees of freedom $v$ = 19 and the level of significance $p$ = 0,95.

It is remarkable that the respondents quite independently marked as the highest risk all kinds of collecting facilities (the source of raw water for a system). This finding is confirmed by the experience from practice; it must be used for the enhanced security and reliability of a scenario of each real SZV in a specific locality from the aspect of exogenous threat (the unintentional and intentional pollution of a collecting area of drinking water). It is necessary to assess the value of a risk index I(*R-fuzzy*)$_i$ in every single case according to a formula (2), and the magnitude $P_i$ to complete and determine by an expert estimate (a responsible person e.g. the administrator of SZV).

## Utility theory and total risk score

Sophisticated preparation of scenarios of the water supply system prevention requires the application of a multi-criteria decision analysis. Generally this issue is solved at work [23]. The method TUKP/TIEQ is a multi-criteria method of the decision analysis of the category of a hard, specific type. It is based on *axiomatic theory* of a cardinal utility MUT, catalogues of criteria and rating curves. Preferably it is used for the basic objective of the determination of the preference of various layouts (comparable scenarios – variants). The adaptability of the method (a random choice from the list of criteria) enables the application either for the risk analysis and the reliability of technology systems, or for the assessment of potential impact and disaster risks within large territorial integrates (process EIA and SEA).

Theoretical background of the TUKP method is made of the conceptions of analysis brought up to the stadium of the decision. According to the author of the theory of value analysis L. D. Miles of 1961, cit. [8], the modification of the determination of *use value* and the *esteem value*, first of all by choosing suitable criteria for generated individual catalogues. We suppose that for a specific number of scenario (variants $V_i$) and for the set of indexes $j$ it is possible to determine all values of parameters (criteria) $P_j$ and partial functions of the use $U_j$, for which it pays:

$$U_j = f_j(P_j)\,, \tag{3}$$

which expresses mathematical form of partial use function. The total function of the use **U** is dependent on the total implication and for its construction we have a set of partial functions of the use $U_j$ . We suppose that the conditions of the preference and use independence of criteria indicators $f_j(P_j)$ are kept. Further we determined the condition that the entire set $V_i$ is a weight or quantitative multiplier, i.e. a relative significance of investigated $P_j$ within the entire set $j$ = 1,2,…,n(y)

$$w_j = \text{const}\ . \tag{4}$$

The value of a total function for a specific scenario (variant) is determined by the value of a multi dimension vector $\mathbf{U_i}$ according to the relation

$$\mathbf{U_i} = \sum_{j=1}^{n} U_j\, w_j \tag{5}$$

.

This shape of the function can be used only in the case that for the set $w_j$ it pays

$$0 \leq w_j \leq 1 \qquad (j = 1, 2, ..., n) \qquad (6)$$

and at the same time

$$\sum_{j=1}^{n} w_j = 1 \qquad (7)$$

.

The paradigm MUT theory appears in many modified applications. For example so called *Total risk score* TRS expresses total numeric expression of a risk based on three parameters, i.e. *the importance factor* IF, *the circumstance factor* $OF_i$ and *the vulnerability factor* $VF_i$; see [7], [18].

*Importance Factor* (IF) expresses the degree of a socio-economic impact of the facility operation calculated as a combination of the facility properties and differentiated weights which are among others

- historical and symbolic importance,
- irreplaceability value,
- importance for regional economy,
- criticality of the utilities connected with the facility,
- military importance,
- exposition of the population or facility.

*Circumstance factor*¨($OF_i$) expresses the degree of probability or potential threat ($i$), calculated with the consideration of differentiated weight for

- level of accessibility,
- level of security,
- visibility or attractivity of a facility,
- the level of publicity,
- the number of threats to the facility in the past.

*Vulnerability factor* ($VF_i$ ) is expressed by the degree of consequences for the facility and the user caused by the occurrence of a threat ($i$), calculated with the consideration of differentiated weight for

- anticipated damage,
- anticipated idle time or the shutdown,
- anticipated number of casualties.

The algorithm of the calculation of a total risk score TRS for a specific facility, entity or a scenario is defined by the formula

$$TRS = (IF) \ \Sigma \left[(OF_i)(VF_i)\right] \qquad (8)$$

and at the same time

$$IF = \Sigma \left[ w_j f_j( x_j ) \right] , \qquad (8a)$$

$$OF = \Sigma \left[ w_j f_j( x_j ) \right] , \qquad (8b)$$

$$VF = \Sigma \left[ w_j f_j( x_j ) \right] , \qquad (8c)$$

where all factors in the formula (8) are calculated using the MUT theory and they gain values in the interval < 0; 1 >. The magnitude $x_j$ is the value of the parameter $j$ ; $f_j(x_j)$ expresses a one-dimension function of the use in the interval < 0; 1 >, symbol $w_j$ means relative importance (norm weight) of parameter $j$ . The symbol Σ declares the summary of all mentioned properties of individual factors IF, OF and VF. The weight of individual properties is determined using the method of pair comparisons in terms of AHP (Analytic Hierarchy Process) with reference to [28]. As long as we work with a team expert method, the averages are applied.

The way of a terrorist risk analysis from the aspect of physical protection of systems of the variable equipment is demonstrated on the development scheme in fig. 4 according to [29]. The groundwork is formed by seven gradual steps.

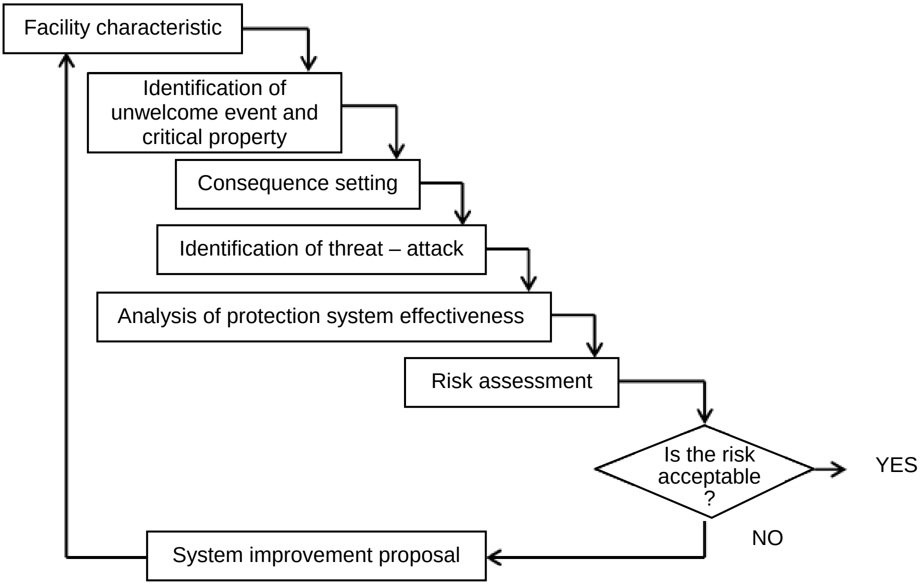


*Fig. 4*
*Methodical scheme of seven gradual steps of a terrorist risk analysis solution for physical equipment or facility; according to [29].*

**How to increase the safety of water systems**

Prevention and mitigation of the exogenous threat to the infrastructure of water supply is generally focused on the impact of a natural disaster, in the CR first of all floods, long-term frost, less frequent storms or tornados, exceptionally earthquakes, etc. The study [22] contains the summary of other exogenous factors affecting the reliability of water supply systems.

*Table 2*
*Unfavorable factors affecting the construction design of water supply systems; according to [22]***.**

| Construction factors | Exogenous factors | Endogenous factors | Operation factors incl. maintenance |
|---|---|---|---|
| Pipes locality | Soil type | Water velocity | Date of failure |
| Profile | Load | Water pressure | Date of repair |
| Length | Groundwater | Water quality | Failure locality |
| Realization year | Stray currents | Hydraulic shocks | Type of failure |
| Pipes material | Treatment of the subsoil | Internal corrosion | Failures history |
| Connecting technology | Seepage | | |
| Inside protection | Other networks | | |
| Outside protection | Road salting | | |
| Pressure class | Temperature (frost) | | |
| Wall thickness | Outside corrosion | | |
| Depth of deposit | | | |
| Treatment of the subsoil | | | |

Growing intensity of terrorist actions accentuates though the anthropogenic threat to exogenous jeopardy of water supply system elements in the full range of the scale of potential attackers. They are vandals, criminals, saboteurs, guerrilla groups and insiders (persons with the knowledge and free access to water supply systems). A higher form of the attack of the insiders is the jeopardy of the electronic control system including the database (SCADA). The classification and categorization of the attackers is important in terms of their motivation, capabilities, differentiation of pursued targets, etc. The prediction of major threats in the future to water supply systems mentions in the first place the category of "sabotage and terrorist attack", encompassing various kinds of hazards, in more details see the database "TECHNEAU Hazard Database" (THDB), cit. [2], [21].

The threat of a terrorist attack and the risk of a terrorist action requires a specific approach to the analysis which differs from a standard concept RA, see theoretical starting points [26]. The core is formed by *conditioned probability and convolution*. For the risk of a terrorist action $R^{ter}$ the probability of a successful terrorist attack must be considered, and the consequence of this attack. The risk of a terrorist action $R^{ter}$ is mathematically defined as a relation of *a threat, vulnerability* and *a consequence*, cit. [3], i.e.

$$Terrorist\ risk_{i,j,k} = Threat_i \star Vulnerability_{i,,j} \star Consequence_{i,j,k}, \qquad (9)$$

**where** *i – specific scenario of jeopardy;*
*j – specific facility or entity;*
*k – specific type of a consequence.*

The threat means “a scenario of jeopardy”, i.e. the threat implicitly includes terrorists´ *knowledge,, characteristics and an attack plan*. The operator “✶” means *convolution*, because the threat, vulnerability and consequences are not figures but probability-like division. *Vulnerability* is defined as the probability of successful jeopardy including consideration of applied protective measures so that the threat and vulnerability together express the probability of a successful terrorist attack.

In a homeland knowledge segment of security science we witness a growing attention to the reliability of a water supply system. The thesis that the main risk point is the distribution network is not according to the experience from abroad. For example the actual manual [13] imputes security priority to valves, aeration and control computer subsystem; the manual predicts redundant configuration with these critical elements, incl. monitoring, response and potential recovery. The emphasis is laid on 100 % redundant configuration of chlorination by a feed pump in order to ensure full uninterrupted operation and the possibility to maintain the system. This measure is fully valid for the alternative source of electric power on which the water supply system is vitally dependent (standby generators). The absence of a concept of the redundancy in water supply systems is criticized by the authors of the study [17], the necessity of brilliant security plans on the redundancy principle is emphasized [14].

With regard to strongly sophisticated attacking ability of actors, at present, effective defensive means are being searched. First of all it is the need for imminent indication of a toxic substance in drinking water. For example the software CANARY Event Detection Software (Sandia National Laboratories) enables the excellent speed of the response approx. 20 to 40 minutes after the first detection of a harmful agent in a distribution system, see [5]. Similarly Early warning systems (EWS), the tool Randomized pollution matrix (RPM), see [20] and Discrete sensor placement, see [1]. In general the rapid detection and the determination of a biological means is incomparably more difficult and complex than the detection of a radiological or chemical attack. For this reason a significant role in the protection against a biological attack consists undoubtedly in intelligence services.

A significant breakthrough in the area of indicators is expected from the implementation of nanotechnology. The outputs of a project co-financed with EK under the title “DINAMICS” (DIagnostic NAnotech and MICrotech Sensors) include among others the “AquaBioTox“, i.e. the application of nanotechnology and a new generation of sensors, see [19]. There they mention the threat of so called “Backflow Attacks” which can be easily applied by an injection pump and a toxic agent on whatever place in the network [32]. From this view a weak point is a fire hydrant which must be freely accessible. As a countermeasure on commercial level, the technological protection Anti-Terrorism Valve (The Davidson ATV) for fire hydrants is offered, see a patent system of anti-terroristic valves of the company Davidson Hydrant Technologies [4].

Conceptual and strategic approaches emphasize the need to evaluate historical contingencies of all kinds including unintentional failure of a human factor. For example in professional literature the attention is drawn to two independent contingencies of chemical contamination of two various systems which is presented in the pattern of a comparative analysis (Tel Aviv, Israel 2001; Camelford, England 1988), see [34]. In the practice, this is the model of a successful terrorist chemical attack on a water supply system with the same coherences and impacts. In homeland conditions there is a countless number of fecal contamination of infiltration areas of drinking water sources as a result of using sewage for farm land with subsequent epidemy of hepatitis.

Physical reliability of water supply systems can be checked through a regular monitoring [16a], [31], see fig. 5.

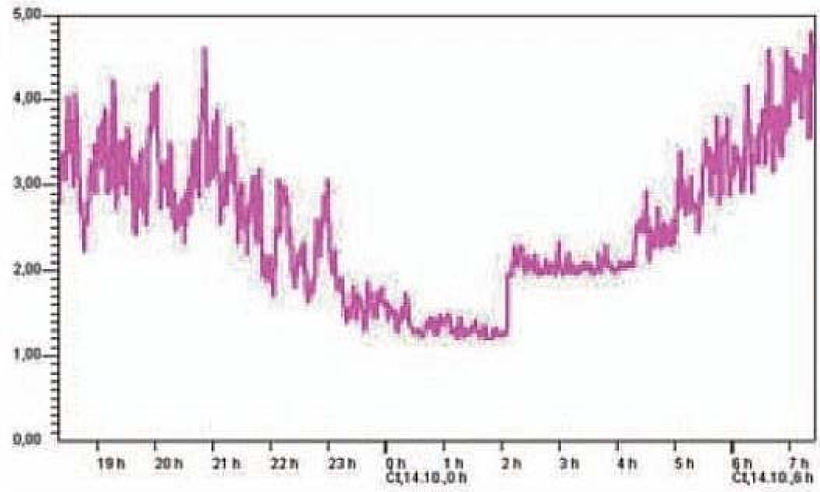


*Fig. 5*
*The instant of the failure occurrence on the pipeline can be indicated through a method of a mobile measurement of the flow rate; according to [16a].*

**Conclusions**

Thorough security and reliability of the water supply system function does not exist. The acceptable size of a risk must be assessed especially from the viewpoint of *the extent, seriousness and time dimension.* The importance of scenarios for the prevention lies in the alternative description of potential prospective situations connected with questions “What-If”. The scenario of the danger changes with the time. The generation and evaluation of scenarios enable to specify subsidiary tools and technologies in order to enhance the anti-terrorist security of water supply systems of the CR.

The ways how to increase the security of water supply systems proceed through the application of a current level of knowledge in the area of the systems theory, decision-making risk analysis and top technologies. The most serious threat is considered the risk of the deterioration of the raw water quality in the system and the destruction of catchment equipment.

**Résumé**

*This paper is focused on the failure of the management and prevention strategies for drinking water systems. Drinking water systems are subjected, to a greater or lesser degree, to hazards. According to the Council directive 98/83/EC, the overall objective of a water supply system is to provide each consumer enough water of good quality. The safety of the water supply network should be considered and the overall costs should be acceptable. The term "enough" water means fulfilling pressure and water demands. The water supply system is built of pipes, valves, storage tanks and pumping stations.*

*In reality it is impossible to make every single structure perfectly immune to the failure. Accordingly, to reduce the possible negative effects on the residents, it is also important to establish measures to quickly fix interrupted water supplies. However, it is difficult to predict all damage that might be caused by natural disasters or a terrorist act to a water supply system. Risk is defined in general as a relation between the likelihood and consequence; conceptually a low likelihood/high consequence event can have the same risk as a high likelihood/low consequence event. For a terrorist act, risk must consider the likelihood of a successful terrorist attack and the consequences of that attack. For a terrorist act, we will mathematically define Risk as a relation among: Threat, Vulnerability, and Consequence. In the context of Equation 7, i denotes a specific threat scenario, j a specific facility, and k a specific type of consequence. The* **"✶"** *operation represents convolution, since Threat, Vulnerability, and Consequence are not numbers but "likelihood" distributions. Vulnerability is defined as the likelihood of success of the threat, considering the protective measures in place; thus, Threat and Vulnerability together provide the likelihood of a successful terrorist attack.*

*Entities operating and maintaining these systems should have strategies directed at reducing the vulnerability of the systems and providing the best possible response once an emergency arises. Resilience is the ability to withstand hazards without incurring loss of service or, if some loss of service cannot be avoided, to restore it in an acceptably short time.*

*This paper provides a brief overview of the concept of the identification and determination of weak and critical elements of drinking water systems. A linguistic variable is defined as a variable whose values are fuzzy variables. In general, fuzziness describes objects or processes that are not amenable to precise definition or precise measurement. The whole purpose of decision analysis is to select the best alternative from the set of available alternatives. This can be*

*reached by application of the axiomatic theory of cardinal utility MUT and by using the additive model of the TIEQ method, too.*

*Scenarios are a significant alternative for the description how the future might unfold. Scenarios are an outline or a model of expected or anticipated sequence of events. The key principle of water policy is the thought that we should deal with the pollution as close to its origin as possible (catchment protection).*

## NOTES:

[1] Hazard or threat scenario is not a mathematical magnitude. This term is used to designate the reality which is considered the basic point when assessing the risk. First of all we must know the *hazard* or the *threat* and also which way it might show up. The scenario of the threat changes with the time.

[2] *The reliability* is a common characteristics of a facility lying in the capability to fulfill required function together with the preservation of values of determined operational indicators in given limits and time based on determined conditions, cit. nomenclative norm (see CSN 01 0101). Reliability cannot be quantified; it is a comprehensive characteristic of a system.

[3] *Redundancy configuration* expresses reserve, surplus, excess, level of backup, information or functional surplus. It is the capability of system elements to take over the functions of elements in the failure; it regards *protective interests of a society.*

[4] *Ecoimpact FORMULA* is a part of the authorized method Fuzzy Logic and Verbal Expressions (FL-VV), see J. Riha [24]; it is a numeric transformation of terms in the form of a code key in terms of "know-how" (not published). The FL-VV method was tested in homeland practice partly for purely construction technical problems, partly for strategic decision making tasks. It was absolutely accepted by the government commission for the assessment of the impact of nuclear power plant Temelin on the environment (process EIA) according to the protocol of Melk (the Government Resolution of the CR no. 65 of January 17, 2001).

## ABBREVIATIONS

| | |
|---|---|
| AHP | Analytic Hierarchy Process |
| ATV | Anti-Terrorism Valve |
| CSU | Czech Statistical Office |
| DINAMICS | DIagnostic NAnotech and MICrotech Sensors |
| EIA | Environmental Impact Assessment |
| ERP | Emergency Response Plan |
| EU | European Union |
| EWS | Early Warning Systems |
| FL-VV | Fuzzy Logic and Verbal Expressions method |
| IF | Importance Factor |
| MUT | Multi-attribute Utility Theory |
| MI CR | Ministry of Interior of the Czech Republic |

| | |
|---|---|
| OF | Occurrence Factor |
| PB | Supporting Points |
| RAM-W | Risk Assessment Methodology for Water Utilities |
| RPM | Randomized Pollution Matrix |
| RS | Risk Score |
| SCADA | Supervisory Control And Data Acquisition |
| SEA | Strategic Environmental Impact Assessment |
| SZV | (Drinking) Water Supply System |
| THDB | TECHNEAU Hazard DataBase |
| TIEQ | Total Index of Environmental Duality |
| TRS | Total Risk Score |
| TUKP | Total Indicator of Environment Quality |
| VF | Vulnerability Factor |
| VV | Verbal Expression |
| WaterISAC | Water Information Sharing and Analysis Center |

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