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Ryszarda IWANEJKO

Institute of Water Supply and Environmental Protection
Cracow University of Technology
Cracow

PRELIMINARY ANALYSIS OF RISKS ATTRIBUTED TO OPERATION OF SMALL SURFACE WATER INTAKES

WSTĘPNA ANALIZA RYZYK ZWIĄZANYCH Z PRACĄ NIEWIELKICH UJĘĆ WODY POWIERZCHNIOWEJ

Na prawidłową pracę ujęcia wody i dotrzymanie dostaw wody do zakładu uzdatniania mają wpływ zarówno źródło wody jak i obiekty techniczne ujęcia. To oznacza, że z pracą ujęcia wody można powiązać kilka rodzajów ryzyk. Są to: ryzyko funkcjonalne (techniczne) związane ze zdarzeniami niesprawności technicznych elementów ujęcia; ryzyko zasobowe związane ze zdarzeniami stałego lub okresowego spadku zasobności źródła lub wzrostem prognozowanego zużycia wody, ryzyko okresowych wystąpień wysokiej mętności, skażeń mikrobiologicznych czy zanieczyszczeń chemicznych. W pracy dla każdego z ryzyk cząstkowych zostanie zaproponowany sposób jego szacowania. Zostanie również zaproponowana metoda wyznaczenia ryzyka globalnego, obejmującego ryzyka cząstkowe. Przedstawiona metodyka umożliwi wyznaczenie ryzyka dla konkretnego ujęcia wody. Podstawą szacowania ryzyka mogą być bądź odpowiednie dane z eksploatacji bądź oceny ekspertów. Przyjęcie poziomów odniesienia (tj. ryzyka akceptowalnego i tolerowanego) umożliwi ocenę ryzyka, a to z kolei może być podstawą do przeprowadzenia ukierunkowanej modernizacji ujęcia, rozważenia decyzji o zakupie wody lub nawet o zmianie źródła wody.

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1. Introduction

Water intake is considered the first and most important element of a water supply system. Many water supply systems located in small municipalities have been continuing operation of their surface water intakes (UjWPow) for at least 40 years. The water intakes were designed to satisfy the conditions existing at that time (water source output, surface water quality) and to meet the actual water demand. Currently, due to the change of the intake operation regime (deterioration of surface water quality) and water quality and quantity standards (increase of consumers' number, more stringent potable water quality criteria after our accession to the EU) some intakes may not be able to operate in a successful way. Their poor performance has obviously an impact on water supply to the consumers (if there is no water reserve within the system) and consumers' safety. Consumers' safety is also affected by performance of other elements of the system such as: water treatment plant or water supply network.

The paper focuses on performance of small communities, with population ranging from 3 000 to 30 000 inhabitants. Moreover, only performance of UjWPow is analyzed and therefore only risks related to the UjWPow are discussed such as: functional risk, resource risk, risk of occurrence of random high water turbidity, microbial or chemical contamination. All they are not the only risks directly related with operation of the UjWPow. One may also investigate the possible risk of deliberate water poisoning by terrorists or people with mental disorders. On the other hand it would seem that such attacks would rather be directed toward larger plants and such risk would be closely related to the current political situation. Therefore, the paper focuses only on the typical types of risks.

2. Partial risks

The above partial risks are strongly related to the poor intake operation i.e. reduced volume of water taken from the river or its unsatisfactory quality. Below a detailed proposal of risk estimation and assessment is presented. Different algorithms are proposed to estimate a risk in terms of its quality (i.e. determination of a relative risk measure considering the most important risk elements). Each algorithm can be described verbally (as a sequence of conditions), as a table or a graph (risk graph, simplified chart). The core element of the proposed risk estimation methods are questions that have to be asked about the range of values of the discussed risk elements and than conclusions about the risk characteristics. Concluding rules that are applied here are as follows: *„if parameters meet the conditions.. ..., then a relative risk measure is... ...”*. It is obvious that the conditions cannot be contradictory but have to be explicit and comprehensive (they have to cover all possible combinations of parameter ranges). The next step involves risk assessment, where one defines the class to which the particular risk should belong. Three widely known risk classes are used here: intolerable risk (RN), tolerable risk (RT) and accepted risk (RA) [2,6]

An intolerable risk is high and it usually involves a lack of safety; it requires an immediate action in order to its reduction regardless of costs (system has to be immediately closed down or modernized).

A tolerable risk involves a moderate risk, that may be temporally accepted, if only the costs of is reduction run high; the ALARP principle (As Low As Reasonably Practicable) applies here.

An accepted risk is small, barely noticeable and their reduction is not required.

The formula “risk reduction” appearing in the above discussion means actions and provisions that have to be made to e.g. eliminate hazards, reduce their occurrence and as where as the burden they cause.

2.1. Functional risk

A functional risk or a technical risk (R_F) involves the possibility of a technical equipment breakdown at a water intake or a power failure at a raw water pump station. The type of breakdown is strongly related to the type of a water intake. All incidents that result in reduction of water volume or a short-time break in intake operation have to be considered. For instance, for a stream intake with pumps such events may involve screens or strainers icing, failure of raw water pump station, strainer fouling due to its poor rinsing etc. At a stream intake with a gravity line, the incident may include the silt sedimentation in a pipe that delivers water to the main well. Magnitude of the failure effects depends both on its duration and reduction of water production.

The risk may be estimated using an algorithm and taking into account the values of major risk parameters. In the paper the algorithm is presented as a table and the major parameters include; reduction of water supply (ΔQ_F), probability or frequency of occurrence (P) and time (T). It is assumed that $\Delta Q_F = \max\{Q_n - Q;0\}$, where Q- water volume, Qn – nominal intake capacity. Overall range of parameter ΔQ was divided into 4 sub-ranges, defining efficiency modes, just like during estimation of the required reliability level. [10]. There are the following modes:

1. NF –functioning reliability (full efficiency), where $Q=Q_n$ so $\Delta Q_F=0$;
2. DF – acceptable functioning (partial efficiency), where $\alpha_{aw} Q_n \leq Q < Q_n$ so $0 < \Delta Q_F \leq (1-\alpha_{aw})Q_n$; usually $\alpha_{aw}=0,7$ is assumed
3. UF – strenuous functioning (limited efficiency); where $\alpha_{gr}Q_n \leq Q < \alpha_{aw}Q_n$ so $(1-\alpha_{aw})Q_n < \Delta Q_F \leq (1-\alpha_{gr})Q_n$; for small communities $\alpha_{gr}=0,25$ is assumed;
4. ZF – non reliable functioning (failure mode), where $Q<\alpha_{gr}Q_n$ so $\Delta Q_F>(1-\alpha_{gr})Q_n$..

Assumption of only four states of efficiency does not limits the methods application; the number may be increased if necessary.

In practice, the best way to estimate risk for all discussed cases of limited water intake efficiency is to use the limiting values of occurrence frequency (n_{aw}), time (T_{aw} [h]) and probability of failure occurrence over a 1 year span (P_{aw}). Some of the limiting values together with the appropriate risk measures are presented in Table 1.

Tab. 1. Proposed limiting values of functional risk parameters

$n_{aw(i)}$ / $T_{aw(i)}$ / $P_{aw(i)}$	Functioning mode		
i- class risk	DF	UF	ZF
R=1	5 / 8 / 3,5E-3	4 / 6 / 1,4E-3	3 / 0,5 / 5,7E-5
R=2	6 / 12 / 5,5E-3	5 / 5 / 2,3E-3	4 / 1 / 1,15E-4
R=3	7 / 18 / 1E-2	6 / 6 / 2,8E-3	6 / 1,5 / 3,5E-4
R=4	8 / 20 / 1,15E-2	8 / 10 / 5,5E-3	10 / 2 / 1,15E-3
R=5	Exceeded at least one parameter of range R=4		

They can be used in the following way: for the observed specific mode of intake efficiency (depending on ΔQ_F) i-class risk is searched (i=1,..4), for which the observed number of failures does not exceed $n_{aw(i)}$ and failure duration does not exceed $T_{aw(i)}$. If also a condition for $P_{aw(i)}$ is met (or: a cumulative time of this mode duration if compared to the whole year does not exceed $P_{aw(i)}$, then R=i, otherwise a higher risk class has to be assumed. From Table 1 it may be concluded that e.g. risk measure of occurrence in a year of 3 events when an intake shut down takes place due to a brief power failures (up to 10 minutes each) or a single event of a intake shut down for a period not longer then 0,5 hr is R=1. However, occurrence of 3 events with a complete intake shut down for a time longer then 0,5 h during the year, generate the value P=1,712E-4 or higher measure of risk (R=3) (according to the values from the table).

The following criteria have been assumed for risk assessment:
- accepted risk (RA), when R=1,
- tolerable risk (RT), when R=2 or 3,
- intolerable risk (RN), when R=4 or 5.

A traditional matrix method in this case:
- seems to be oversimplified; it does not consider major diversification of events; specification of classes would have to be more complex (defined in a form of accepted alternative occurrence of events or in a form of acceptable exclusive occurrence of events), and therefore it would be difficult for an every day use.
- may not estimate risk according to hazard and the magnitude of its possible outcome; a product of an acceptable frequency of occurrence n_{aw} and time T_{aw} gives the total time of the specific mode over the year – it seems obvious that the occurrence of the same mode e.g. $\Delta Q=0{,}5Qn$ observed 5 times a year, each time for 10 hrs and once a year for 50 hrs requires quite different interpretation.

Example: The following sequence of technical failures was observed at the water intake:

A1: $\Delta Q_F=0{,}2Qn$ (mode DF), once for 10 hrs;
A2: $\Delta Q_F=0{,}15Qn$ (mode DF); twice for 3 hrs,
A3: $\Delta Q_F=0{,}5Qn$ (mode UF); 4 times for 5 hrs;
A4: $\Delta Q_F=0{,}9Qn$ (mode ZF); twice for 1 hrs.

In Table 1 for a case of failure A1 (e.g. mode DF) limits of $T_{aw}\le 12$ hrs and $n_{aw}\le 6$ were found and the probability condition was verified i.e. $P=10/(24\cdot 365)=1{,}14E\text{-}3\le P_{aw}$. Therefore, it was found that R(A1)=2. In similar way values of R(A2)=1, R(A3)=2 and R(A4)=3 were found. Finally, the highest value of R=3 was assumed which means that the functional risk at this water intake is tolerable.

2.2. Resource risk

A resource risk (R_Z) comes from the fact that the required volume of water cannot be withdrawn from a river (on permanent or temporary basis). It depends on the output of available water resources (following the water permit limitations) and a planned water usage.

The resource risk may be defined in the same way and with the same parameters as R_F., and a parameter of an intake capacity reduction ΔQ_Z should be assumed as $\Delta Q_Z = \max\{Q_n - Q_{pwp};0\}$, where Q_{pwp} – maximum value according to the water permit. The Mode ZF (defined with R_F) usually refers to low water levels but for some specific water intakes it may occur due to some natural causes (e.g. at a shore intake, due to very high flows or flooding resulting in an intake drainage fouling; at a stream intake due to icing).

High fluctuations of a river flow rate have an impact on prospective changes of number and nature of water consumers or a lowering trend of water consumption, generating a dynamic and strategic risk. It may be assessed as a current risk or a risk of a varying time span (e.g. for next 5 or 10 years). Hypothetical and simplified variability of parameter ΔQ_Z, used for evaluation of a dynamic risk for different times is presented in Figure.1.

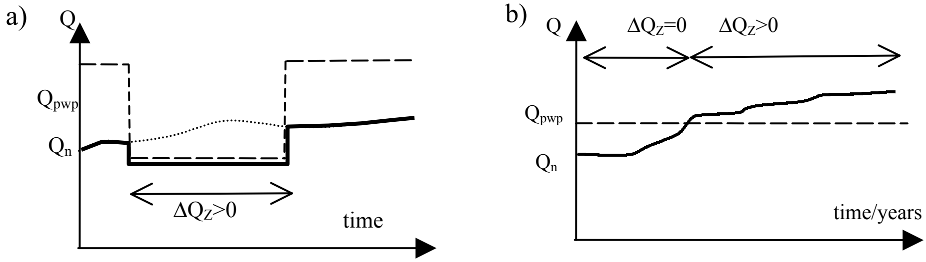


Fig.1. Variability of parameter ΔQ_Z in (a) short (b) long period of time

2.3. High turbidity risk

Risk of occurrence of a high turbidity at the water source (R_M) most of the time is related to intensive precipitation. High turbidity of surface water may result in a lower water supply and deterioration of water quality at the consumers. Therefore, the risk in this case has to be considered both from qualitative and quantitative perspective.

Risk assessment is performed using a risk graph. The risk graph is a simple indicative method where the values are assigned to some risk parameters while the other parameters have only their importance assigned. Also the number of classes of different risk parameters may be different. The method is very useful when classes of risk (RA, RT, RN) cannot be directly related to the product of parameter values (as in the matrix method).

Three principal parameters are proposed to be considered at the water intake:

- turbidity in a river (M),
- duration of high turbidity (T)
- probability (frequency) of the occurrence (P).

At some specific situation some other parameters should also be included. For instance, if a stream intake operates a raw water reservoir that can temporary withhold water of a low turbidity, than an additional parameter of hazard avoiding should be considered (U).

Figure 2 presents a graph of a high turbidity risk for e.g. a stream intake. To estimate the risk for a stream intake the following risk parameters classes were assumed:

- for surface water turbidity (classes are related to the water treatment plant equipment, technology and investment costs):
  - M1 – up to 1 000 NTU – water turbidity can be removed during the treatment process and water volume is Qn, ,
  - M2 – up to 1 4000 NTU – water turbidity can be removed if water production is reduced to $0{,}7Q_n$,
  - M3 – up to 2 000 NTU – during treatment of water volume of 0,7Qn turbidity may be lowered down to 20 mg SiO_2 (about 9 NTU) (the maximum value accepted by the National Institute of Hygiene in emergency situations) [7],

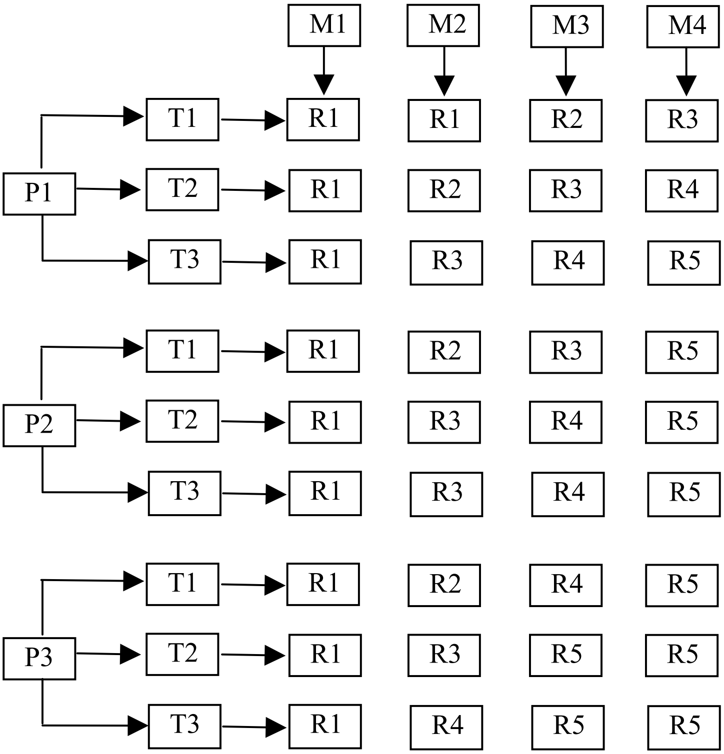
M4 – above 2 000 NTU – the water intake should be closed down,

- for probabilities of occurrence (frequency):
  P1 – no more then 3 times a year,
  P2 – from 4 to 10 times a year,
  P3 – more often then 10 times a year,
- for duration:
  T1 – up to 8 hrs,
  T2 – up to 16 hrs,
  T3 – over 16 hrs.

Obviously, the turbidity classes Mi may differ for other types of intakes. For drainage water intakes (or combined drainage/stream or drainage/threshold intakes) turbidity classes may additionally acknowledge the limiting turbidity value (150 NTU), that causes fouling of the drainage intake.

It is proposed that the risk is:

- acceptable (RA), if R=R1,
- tolerable (RT), if R=R2 or R3,
- intolerable, if R=R4 or R5.



		M1	M2	M3	M4
P1	T1	R1	R1	R2	R3
	T2	R1	R2	R3	R4
	T3	R1	R3	R4	R5
P2	T1	R1	R2	R3	R5
	T2	R1	R3	R4	R5
	T3	R1	R3	R4	R5
P3	T1	R1	R2	R4	R5
	T2	R1	R3	R5	R5
	T3	R1	R4	R5	R5

Fig. 2. Graph of a high turbidity risk

Example: The following high turbidity values were observed at the stream intake over the last year:

1) 800 NTU: 3 times, for: 6 hrs, 20 hrs and 36 hrs, respectively,
2) 1500 NTU – once for 12 hrs.

In the first case (parameters classes are M1,P1, T1 and twice T3) the risk is R=R1. In the second case (classes: M3, P1, T1) the risk is R=R3, which means that for this intake it is tolerable.

2.4. Microbial risk

A microbial risk (R_{Mb}) originates from intake of water contaminated with bacteria. Such contamination may be detected only after some time needed to cultivate the microbial colonies (usually after 1-2 days). Introduction of sophisticated identification methods e.g. a molecular biology may shorten this time substantially but such methods are very expensive and hardly used by the any water works. Consumption of even small amount of contaminated water may have severe health effects. It is possible that microbial contamination of water may take place more then once at the same location (e.g. *Clostridium perfringens* – Nowy Targ , spring 2003 and 2005), though most of the waterborne diseases (e.g. cryptosporidiosum) have been reported in different cities. The presented in literature propositions of risk assessment are related to treated water quality [7].

Here, we propose a simple relation between a risk and parameter Z that defines the possibility of hazard at the water intake. Typical classes of hazard (1÷5) with their specifications are presented in Table 2. During determination of the parameter Z value for the specific intake all possible hazards have to be considered and as the final measure the highest class has to be selected.

Tab. 3. The proposed classes of microbial hazards.

Class of Z	Specification
1	Upstream of the intake no hazardous plants or the existing WWTP operates at the minimal risk of failure (technological line with stand by units, extra capacity, by-pass of a biological stage, emergency power supply, well trained and responsible staff); even during intensive rains the probability of exceeding the capacity reserve is small (less then 0,05 in a year)
2	Upstream the intake the WWTP is located; a possible discharge of pollutants that inhibit the treatment process e.g. from electroplating, tannery, gas stations (e.g. cadmium, chromium, nickel, oil derivatives); no by-pass for a biological stage; single energy source; probability of exceeding the plant capacity is small (from 0,05 to 0,1 in a year)
3	Upstream the intake the WWTP is located; sludge is deposited close to the river and may be washed down during intensive rains; technological units without a reserve capacity; probability of exceeding the plant capacity is moderate (from 0,1 to 0,5 in a year)
4	Upstream the intake the WWTP is located; technological units without a reserve capacity; probability of exceeding the plant capacity is rather high (0,5 ÷ 0,9 in a year); at least one case of water contamination occurred in past.
5	Upstream the intake the WWTP is located; poorly trained staff; probability of exceeding the plant capacity is high (over 0,9 in a year))

In classification (see Table 2) only hazards related to the presence of the wastewater treatment plant were considered. Other hazards that may be caused by facilities located within the catchment and upstream from the intake e.g. hospitals with contagious wards (since Poland's accession to the EU the hospitals are required to have their own wastewater treatment plants) or agricultural areas (deposition of fertilizers or application of manure causes an surface runoff during fall rains or snow melting period) were not discussed. The first case may be classified as hazard class 1 while the second as class 4.

To asses the risk class (RA, RT, RN) for the specific community one should take into account the type of disinfectant used at the water treatment plant (eg. chlorine requires more stringent class then chlorine dioxide) and other safety provisions (as membranes used at Sucha Beskidzka). For most communities it is assumed that the risk is:

- acceptable (RA), if Z=1,
- tolerable (RT), if Z=2 or 3,
- intolerable, if Z=4 or 5.

2.5. Chemical risk

Chemical risks (R_{Ch}) involve contamination of a water source with chemical substances. Similar like in case of a high turbidity it may result in reduction of water supply, shut down of the intake (if contamination was detected early enough) or water quality deterioration (if contamination was not detected). Literature provides some methods of chemical risk assessment for potable water quality [7].

Chemical risk should be assessed separately for every type of contaminant detected in raw water. In the simplest case (no synergistic effects between the contaminants) the maximum risk from all single risks should be selected as the overall chemical risk.

Here, a chemical risk for a single contaminants is proposed to be estimated using an algorithm and depending on: efficiency of contaminant removal at the water treatment plant (U) , its concentration in surface water (S_{sur}) and in consequence in treated water (S_{uzd}). The algorithm conditions are presented below:

1. if contaminants are considered as totally removable (for a wide range of concentrations S_{sur}) then R=1;
2. if contaminants are considered as partially removable, and its concentration in raw water:
    a. allows its reduction to the value $S_{uzd} \leq NDS$ (i.e. the maximum allowable concentration acceptable by the current water quality standards [8]), then R=2,
    b. allows its reduction to the value $S_{uzd} \leq S_{PZH}$ (i.e. the maximum allowable concentration accepted by the National Institute of Hygiene in emergency situations [7]), then R=2,
    c. does not allow to reduce concentration even down to S_{PZH}, then R=3
3. if contaminants are considered as not-removable, and its concentration in raw water:
    a. does not exceed $S_{sur} \leq NDS$, then R=1,
    b. does not exceed $S_{sur} \leq S_{PZH}$, then R=2,
    c. exceeds S_{PZH}, then R=3,
4. if contaminants are considered as no threshold contaminant (remains harmful regardless of its concentration), then R=3.

Risk assessment criteria are simple. The risk is:

- acceptable, if R=1,
- tolerable, if R=2,
- intolerable, if R=3.

The proposed risk parameters do not include so called system resistance built up by water quality monitoring (e.g. automatic early warning stations [9]). Resistance should rather be analyzed while assessing risk of the water supply system, as a whole unit The detailed analysis of a chemical risk may also include other contaminants that are not analyzed in the laboratory but though may possibly appear in water; its specifics and health effects should be investigated as well.

3. Global risk

Assessment of the risk that incorporates all other partial risks can be performed in different ways. For instance, the global risk may be determined as:

- the maximum value from among the partial risks: $R = \max\{R_Z, R_F, R_M, R_{Mb}, R_{Ch}\}$, if no synergistic effect between different types of contaminants is observed,
- product of partial risks, if a synergistic effect for different types of contaminants is possible; the method requires to determine the classes of RA and RT for a wider scale of a global risk (e.g. for five partial risks, each of them may be acceptable, tolerable or intolerable, the global risk may take values from 1 to 3^5),
- sum (regular or weighted) of partial risks; is possible to differentiate the weight of specific partial risks; in this case the most difficult part is to correctly assign weights as to truly reflect the level of the global risk.

In the paper the global risk is calculated based on the algorithm defined by the following conditions:

1. if all partial risks are acceptable then the global risk is acceptable,
2. if no more then three partial risks are tolerable then the global risk is tolerable
3. if more then three partial risks are tolerable then the global risk is intolerable
4. if at least one partial risk is intolerable then the global risk is intolerable.

The advantage of the method is that new conditions may be easily added or changed. Example: The ranges of partial risks are presented as series: (R_F, R_Z, R_M, R_{Mb}, R_{Ch}). For two cases: (1,1,2,1,2) and (1,1,1,1,3) the sum of relative measures of partial risks is 7. Using the presented algorithm it may be concluded that the global risk is tolerable or intolerable, respectively.

4. Summary

In the paper the risk is related the situation when the UjWPow cannot perform its operation due to so called hazardous events. They may be caused by design errors, change of operational conditions, presence of hazardous facilities or occurrence some hazardous events upstream of the intake, natural catastrophes, etc. The hazards cannot be entirely eliminated and therefore it is necessary to perform their identification and risk assessment. The risk identification process itself should include events already widely known (which took place in past) as well as the new ones, which may possibly happen (not observed in this system, yet).

Basis for risk assessment are empirical data gathered during intake operation (if operational conditions remain constant and the data base is representative) or an expert opinion, (if operational conditions have changed or for potential unknown hazards that occurred very rarely). Change of operational conditions is due to addition or removal of a hazardous unit or modernization of the water intake facility. In the paper the limits of risk (RA,RT,RN) classes have been determined for small communities (from 3 000 to 30 000 people) with one water supply system and with no reservoir for raw and treated water (V_{aw}). They should not be acknowledged as biding. In a similar way the classes of parameters and risk classes for other categories of communities may be developed.

The paper proposes the algorithms to assess partial risks that seem to offer advantage over traditional matrix methods, in which the relative risk measure, according to the Farmer's principle, depends directly on a product of risk parameters. Here, the algorithms provide a better diversification of the parameters (easy description, varying number of class of different parameters, some parameters may be defined numerically while others just in a descriptive way).

The risk assessment performed in the paper gives a rational basis for a modernization of the water supply system. A possible provisions taken to reduce risk may include: modernization of water intake, protection of intake from incidental contamination [6], modernization of water treatment plant and /or alternative treatment technologies [6], safety layers [4], raw water reservoir[1, 5], additional water source as reserve, water purchase [3].

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