Risk assessment for drinking water production: assessing the potential risk due to the presence of *Cryptosporidium* oocysts in water

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Abstract This paper presents an approach for assessing the risk of producing non-compliant drinking water (i.e. one of the quality parameters exceeds the standards fixed by legislation), taking into account the quality parameters of raw water and the process line of the treatment plant (technology, different failure mode and corresponding failure rate). Firstly, nominal and degraded modes of each step of the treatment line are analysed, in order to obtain transfer functions (which give output concentration of parameters in function of the input concentration) for each step of the treatment and each quality parameter, in nominal and degraded functioning. The transfer function of the whole treatment process can thereby be obtained by combination of transfer function of each step, and failure conditions of the whole treatment process and corresponding degraded global transfer function could be determined. Secondly, an inversion of both global function (nominal and degraded) permits to estimate probability for the resource to exceed thresholds fixed by regulation (in that case, a scenario of non-compliant drinking water exists), and to obtain a compliant water availability. Finally, this paper presents a software tool realised to evaluate the risk of non-compliant produced water, using the described methodology. Finally, an approach of risk assessment for *Cryptosporidium* is also presented. This method allows identification and sets priorities for utilities presenting the highest risk.

Keywords *Cryptosporidium*; risk assessment; software

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Introduction

This paper presents an approach for assessing the risk of producing non-compliant drinking water, a fundamental aspect to take into account to design a water treatment plant. Some other aspects of risk assessment in the drinking water domain (settling efficiency optimisation and unavailability due to network failures) have been developed in another paper (Schön *et al*., 2000). This methodology, according to the final use (drinking water production), is important to bring under control the risk that one of the quality parameters exceeds the standards fixed by contract clauses or by health legislation.

This risk assessment method must take into account:

- The quality parameters of the raw water: the distribution probability of their peaks consecutive to climatic events, pollution, etc.
- The process line of the treatment plant, namely the successive steps of the treatment process and their types.
- The technology of the different treatment steps, the different possible failure modes and the corresponding failure rate.

The risk will be assessed within quantitative indicators (the probability for each parameter to exceed the maximal threshold). These indicators will be synthesised in an unique indicator: the global availability of the drinking water (percentage of total production time where produced water respects the standards) which enables an estimation of possible contractual penalties.

Definition of treatment processes and corresponding transfer functions in nominal mode

To characterise the water quality (ability to human consumption) more than 60 parameters (physical–chemical, bacteriological, etc.) are defined by the authorities responsible for sanitary safety. For the needs of this study, we only consider about 20 parameters (the most critical for human health).

These parameters (some of them being obviously interdependent but in most cases in a complex manner) can be grouped in four families, namely:

- undesirable characteristics (turbidity, coloration, iron/manganese content);
- physical–chemical parameters (dissolves salts, arsenic, fluorides);
- microbiological parameters (algae, algae's toxins, fecal coliforms, *Giardia*, *Cryptosporidium*);
- human activity indicators (ammonium, nitrates, hydrocarbons, phenol, pesticides, detergents, polycyclic aromatic hydrocarbons).

To take into account these different types of resource, different treatment processes have been identified. Each process involves successive treatment steps, which can be: preoxidation, settling, sand filtration, Granular Active Carbon (GAC) filtration, ozonisation, and chlorination.

The approach then consists of estimating a transfer function for each treatment step and for each quality parameter. This transfer function gives the output concentration C_{output} as a function of the input concentration C_{input} for the corresponding quality parameter and is, in most cases (exceptions are undesirables components that can be introduced in treated water by the treatment step, such as aluminium salts used as coagulants in settling steps) equivalent to a reduction factor ρ, a 100% reduction factor corresponding to the complete elimination of the corresponding component, such as:

$$C_{output} = (1 - \rho) \times C_{output} \quad (1)$$

This reduction factor, however, can be dependent on the input concentration (the lower is the input concentration, the better is the treatment step efficiency) inducing non-linearity in the preceding relationship. In such cases we define in our model different input concentration ranges, and approximate the real transfer function by an affine function inside each range (Figure 1). In some cases, when a quality parameter exceeds a certain threshold, the treatment step becomes completely inefficient and the corresponding reduction factor is therefore considered as 0%.

The parameters calculated at the output of a step are those at the next step and the parameters at the output of the whole process can then be calculated step by step.

This approach implies two underlying hypotheses.

- The treatment steps are considered as independent. This is a quite realistic approximation but in some cases a given step (e.g. pre-oxidation) can influence the efficiency of a subsequent one (e.g. settling).
- The transfer function is considered as a constant function. That means that for devices with a limited treatment capacity (for example, an active carbon filter can absorb a given quantity of impurities and is inefficient because it is saturated beyond this threshold), rigorous maintenance actions are performed.

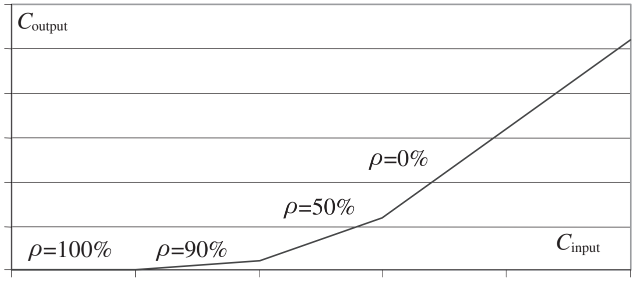


Figure 1 Approximation of a non-linear transfer function

Failure mode analysis and degraded transfer functions

The second step of the approach consists of determining the different failure modes that can affect the different treatment steps. Failure Modes Effects and Criticality Analysis (FMECA) are performed for each step, using the experience of experts in treatment plant operation and maintenance.

The results of these analyses are synthesised in FMECA arrays as shown in Table 1, allowing clear identification of each failure mode:

- the possible cause;
- the failure rate λ (in hours^{-1}) as known by experience on similar equipment in operation;
- the detection means (immediate detection because the failure strongly affects a quality parameter continuously monitored, detection only during maintenance action, etc.);
- the corresponding latent period, T, in hours (maximum duration of water production continuation in presence of that failure);
- the effects on the quality parameter at the output of the treatment step (qualitative);
- the degraded transfer function for parameters affected by the failure (quantitative): equivalent to the definition for the failure mode of a degraded reduction factor ρ_{degraded} smaller or equal to the nominal reduction factor ρ_{nominal}, and which can also depend on the input concentration.

Failures that never occurred in operation but which would be serious are nevertheless mentioned in analysis with a special indication "never encountered" instead of the probability occurrence.

The detection mean and latent period columns allow determination of the corresponding unavailability $U = \lambda T$ (probability of encountering the corresponding degraded transfer function) used to determine the global drinking water unavailability (see hereafter§5). They are also useful to identify possible multiple failure scenarios (the longer is the latent period of a failure, the most probable is its combination with another failure).

Figure 2 illustrates the case of a treatment step becoming completely inefficient consecutively to the failure, like the GAC filtration saturation mentioned above.

Table 1 Example of a FMECA array

Failure	Cause	Failure rate λ (h^{-1})	Detection	Latency *T* (h)	Effects	Degraded transfer functions
Filtration inefficient	Filter saturation	Never encountered[a]	Immediate[b]	Negligible[c]	No filtration effect	Turbidity reduction factor becomes 0%

[a] With an accurate maintenance policy
[b] The quality degradation of the produced water is immediately detected by sensors
[c] The operating instruction recommend to stop the production in that case

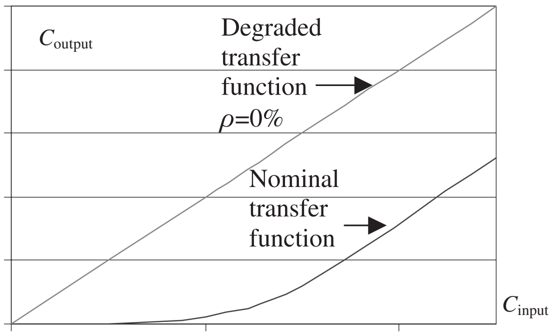


Figure 2 Example of a transfer function in nominal mode and in degraded mode (failure mode)

Definition of raw water quality

The third step of the methodology consists of defining the distribution function of each quality parameter of the raw water (the probability that the corresponding concentration exceeds a value as a function of this value). This step involves specialists of the resource, must take into account many parameters (climatic, hydrogeological, etc.) and is therefore quite complex. For that reason, it is generally impossible to completely define the distribution function, and this step is limited to an estimation of probabilities for each parameter of the raw water, to exceed some critical thresholds determined by "retro-propagation" of the different thresholds defined for the treated water (final product distributed to consumers). More precisely this step consists of the following tasks:

- Determining the transfer function of the *whole* treatment process obtained by combination of the transfer function of each step, the water at the output of a step being the input of the next step. Because of non-linearity, this combination in most cases is not commutative.
- Identification for each quality parameter of the treated water (final product) the different pertinent thresholds: health legislation imposes a value, but the company often has its own more constraining quality targets.
- Inversion of all global transfer functions (nominal and degraded modes), and applying these inverse functions on all thresholds previously identified. The result is a series of thresholds now relative to raw water quality: if the resource quality parameters exceed one of them, a scenario of non-compliant treated water exists. According to which function and which value were used in the calculation of the concerned threshold, this non-compliance is relative to health legislation or internal targets and occurs in a nominal or degraded mode.
- Estimation of the probability for the resource to exceed each of these thresholds. The result is an approximation of the distribution functions for each quality parameter, which contains exactly the probability values needed for the continuation of the study (Figure 3).

In this example (Figure 3), two modes for the treatment plant (nominal and degraded) and two type of treated water quality targets (health legislation and internal) are taken into account. If the raw water quality parameter concentration exceeds the value (horizontal axis), the corresponding target for the corresponding mode is not respected. The probability estimation can be read vertically.

Determination of compliant water availability

The last step of the methodology consists of synthesising the scenarios leading to the production of water which does not respect a quality standard (legal target or internal target),

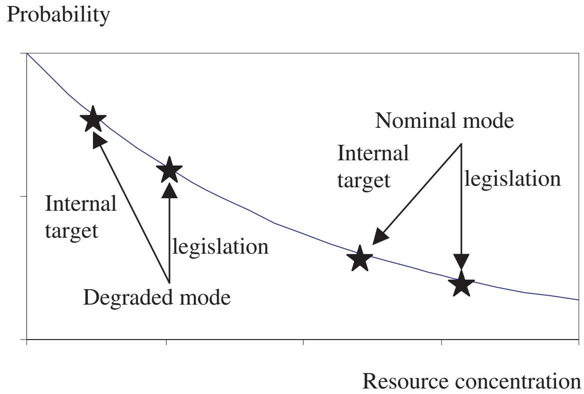


Figure 3 Example of a raw water parameter distribution function

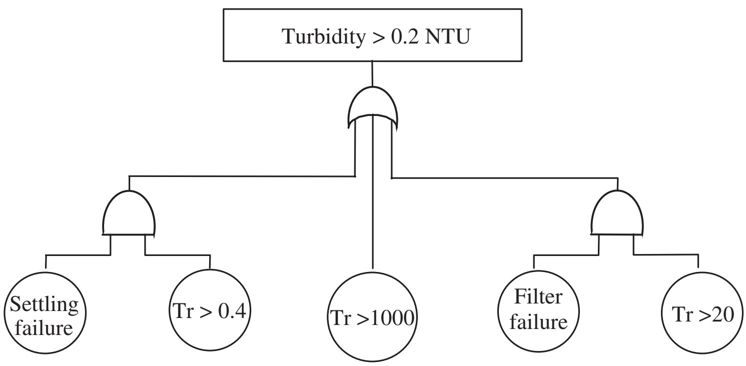
and to obtain the corresponding probability (contribution to the global unavailability of compliant water).

For each quality standard a fault tree (Limnios 1992) is elaborated using the results of the preceding step. Each fault tree regroups at least:

- a single event scenario depending only on the resource (the corresponding parameter exceeds the critical threshold where the treatment line *in nominal mode* is no more able to produce compliant water)
- one or more multiple (generally two) event scenarios: a (generally single) failure of the treatment line, and one resource-dependent event (the corresponding parameter exceeds the threshold where the treatment line *for this failure scenario* is no more able to produce compliant water).

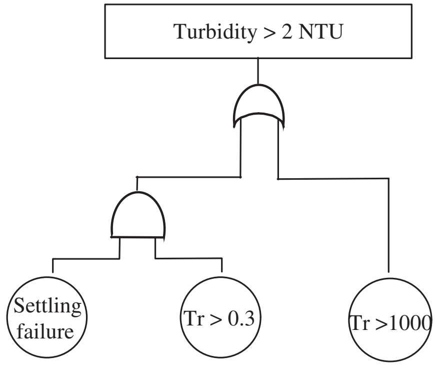
Two examples of such fault trees are shown in Figures 4 and 5 respectively for internal and legislation targets of the turbidity parameter.

Finally, the probability of each fault tree top event is calculated using the probability of the elementary events (unavailability of treatment steps and probability for the resource to exceed the different thresholds). Table 2 shows an example (estimated values, because real values from operation are not yet available) of these elementary events' probability.



Tr = Resource turbidity

Figure 4 Example of a fault tree with a non-compliance to an internal target as top event



Tr = Resource turbidity

Figure 5 Example of a fault tree with a non-compliance to a legislation target as top event

Table 2 Probability of elementary event

Event	Probability
Resource turbidity > 1,000	2.7×10^{-4} (1 day/10 years)
Resource turbidity > 20	0.98
Resource turbidity > 3	0.99
Resource turbidity > 0.4	1
Filtration unavailability	0.01
Settling unavailability	2.7×10^{-3} (1 day/year)

With these data we finally obtain the fault tree top event probabilities:

Treated water turbidity > 0.2 (internal target): 5 days/year
Treated water turbidity > 2 (legislation): 1 day/year

The global unavailability (water not compliant to internal targets/respectively legislation targets) is simply obtained by addition of the contribution relative to each quality parameter.

Example of risk assessment for *Cryptosporidium*

Introduction

The occurrence of cryptosporidiosis has been extensively reported in the literature. Research has highlighted the ability of oocysts of *Cryptosporidium* to survive in the aquatic environment and their tolerance of the chemical disinfection processes used in conventional water treatment. Today, *Cryptosporidium* is only regulated in the United Kingdom. The Drinking Water Inspectorate (DWI) requires a level of less than 10 oocysts/100 L; it is a criminal offense if oocyst concentrations are greater than or equal to 10/100 L. The United States Environmental Protection Agency (USEPA) is currently revisiting the Surface Water Treatment Rule which provides guidelines on *Giardia* and turbidity for surface and groundwater sources under the influence of surface water. To establish the regulation on *Cryptosporidium*, the USEPA is conducting an extensive monitoring program on various source waters thru the Information Collection Rule (ICR). For France, the new European Standards do not require any maximum value for *Cryptosporidium* levels in the treated waters. However, there is a clear need for the water industry to develop tools in order to evaluate the parasite risk and consequently take the appropriate corrective actions. The objective of the paper is to present the Ondeo Service approach, which is currently on-going at various facilities located in France, the United States, the UK, the Czech Republic, and Asia.

Risk assessment approach

The risk assessment approach developed by Ondeo Services is briefly described below. The approach is similar to the procedure discuss above (simplified) and is primarily based on three levels of risk acceptance, combined with the treatment train performance evaluation, and potential source water contamination. The levels of risk acceptance are based on the USEPA infectivity model, the analytical detection limit of the microorganism, and the UK regulations. The USEPA model is based on an evaluation of the infectivity of *Cryptosporidium*, according to work by Dupont *et al.* (1995) involving 29 healthy volunteers. The study showed that the exponential model is the one most representative of the dose/response function associated with *Cryptosporidium*. The function establishes the correlation between the predicted proportion of affected subjects and the average ingested dose of cysts. This model (Eq. (3)) was validated on the Milwaukee epidemic of 1993 (Haas *et al.*, 1996).

$$p = 1 - \exp\left(-\frac{365 \times R \times V \times C}{1/p \times A} \right) \tag{3}$$

where:
P = level of infested persons
R = analytical method recovery
V = water volume being ingested
C = oocysts concentration in raw water
p = probability of oocyst survival in human body
A = average log removal by treatment train

From Haas *et al.* (1994), the most probable value for p is $4{,}673 \times 10^{-3}$. Nahrstedt and Gimbel (1996) reported that the analytical method efficiency of 25% would be a good estimate. In the following calculations, the value for V of a 2 L/day person was used.

The UK regulation level has been defined by the DWI according to the observed concentration during outbreak events.

A two-dimensional plane coordinate system was therefore built. A low risk was defined according to the USEPA model assuming an annual risk of 10^{-4} (i.e. 3×10^{-3} oocysts/100 L in treated water). The medium and high risks were based on the detection limit of 1 oocyst/100 L in treated water for the analytical method and on the UK approach of 10 oocysts/100 L in treated water, respectively.

As discussed above, raw water classes were identified. For *Cryptosporidium* specific risk, six classes were identified as shown in Figure 6. The source waters were ranked with associated maximum levels of oocysts. The levels of oocysts were obtained from internal Ondeo Services databases. The source waters ranged from groundwater with non detected oocysts to surface water with 105/100 L oocysts.

The treatment efficiencies of *Cryptosporidium* oocysts were established from data available from the literature and intern Ondeo Services databases. As presented in Figure 7, various removal efficiencies were attributed to the processes being used at a facility. It should be noted that each process step removal efficiency was summed in order to obtain the complete process train removal efficiency. For example, a process train comprising of a sedimentation followed by a filtration was credited 4 logs (1+3).

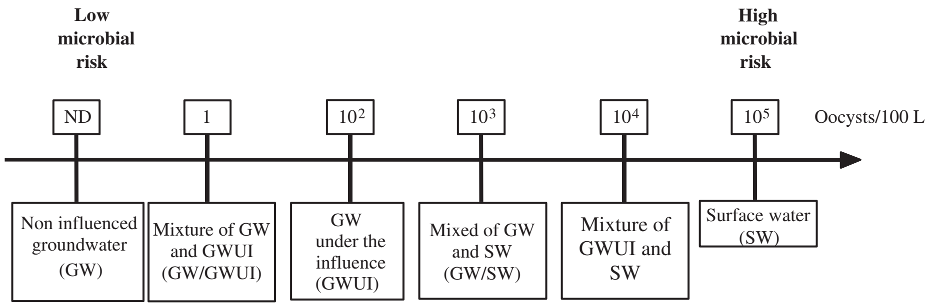
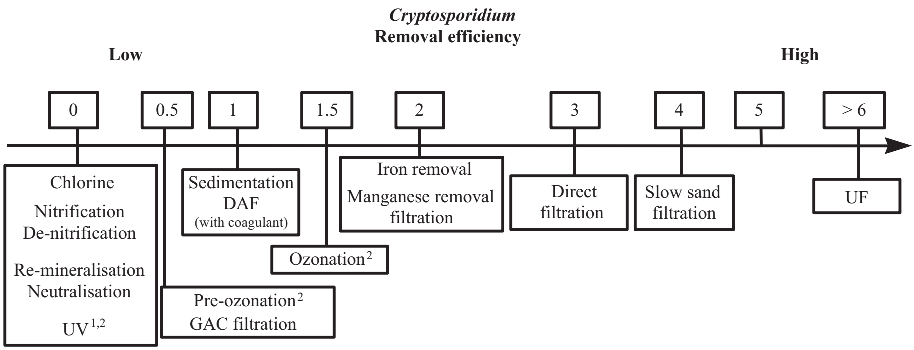


Figure 6 Water classes identified for *Cryptosporidium* risk assessment



[1] On-going studies show that *Cryptosporidium* inactivation could be feasible with UV processes at low doses.
[2] Inactivation efficiency only detectable using infectivity or viability analytical methods (not a physical removal)

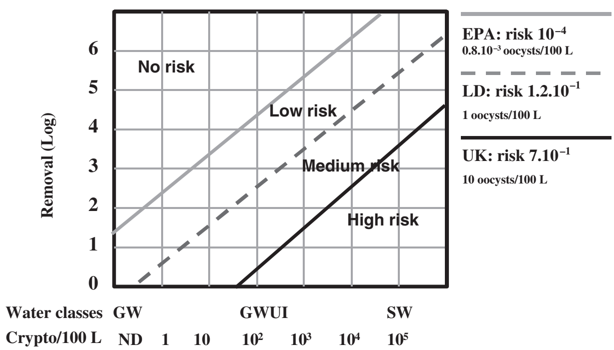
Figure 7 *Cryptosporidium* oocyst removal for various unit processes (inactivation or physical removal)

For this first *Cryptosporidium* risk assessment, the process failure presented above was not included. However, this should be further taken into account when a risk is identified.

The drinking water production facilities of Ondeo Services were distributed along the two-dimensional plane coordinate system, which links the oocysts concentrations (type of resource) with the removal rates achieved by the associated treatment lines (Figure 8).

Summary and recommendations

For treatment plants assigned to the medium and high risk categories, it is important to verify that all facilities are operating under best practices to ensure minimum risk. In addition,



ND = non detected

Figure 8 Risk schematic diagram

intensive monitoring is required for the high-risk category sites. It also involves microbial analysis (IFA method USEPA 1623) on cumulative 100 L samples of treated water taken over a 24 hour operating period of the production units. If positive samples, *C. parvum* species (pathogen for human) are then searched for using a molecular biology technique. These results allow Ondeo Services to identify the facilities for which alternative source waters should be sought or additional investments for treatment facilities made as a priority in relation with the health authorities. In addition, process failure analyses should be implemented to truly evaluate facilities in the near border of risk classes.

Conclusion and perspectives

This paper has presented an efficient implementation for a risk analysis model for a water treatment plant. This implementation enables the quantification of the risk of non-compliant produced water. Twenty of the most important quality parameters are analysed and the user can design the process to manage the risk that one of these parameters exceeds the standard.

We presented a specific approach using fault trees in order to quantify the risk of non-compliant produced water. The generation and the quantification of the fault tree has been packaged in a prototype; users design their process line by choosing the appropriate treatment boxes (colouration, settling, ultrafiltration, iron removal, etc.) and the dosage of reactivity.

In addition, a similar simplified approach being applied for parameters such as *Cryptosporidium* was found to be useful for setting priorities in implementation of corrective actions, ranging from close water quality monitoring to capital investment.

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