RISK ASSESSMENT FOR DRINKING WATER PRODUCTION PROCESS

GESTION DES RISQUES DES USINES DE TRAITEMENT D'EAU POTABLE

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The purpose of this paper is to propose an approach for assessing the risk of producing non-compliant drinking water (i.e. one of the quality parameter 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 modes and corresponding failure rates).
Firstly, nominal and degraded modes of each step of the treatment line are analyzed, in order to obtain transfer functions (which give output concentration of parameters as a 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 functions of each step, and failure conditions of the whole treatment process and corresponding degraded global transfer function could be determined.
Secondly, an inversion of global functions (nominal mode and all degraded modes) enables estimation of probability for the resource to exceed thresholds fixed by regulation (in this case, a scenario of non-compliant drinking water exists), and to obtain a compliant water availability. Finally, this paper presents a software tool developed to evaluate the risk of non-compliant produced water, using the described methodology.

1. Introduction

The purpose of this paper is to propose an approach for assessing the risk of producing non-compliant drinking water, a fundamental aspect to take into account when designing a water treatment plant. Some other aspects of risk assessment in the drinking water domain (settling efficiency optimization and unavailability due to network failures) have been developed in another paper [1]. 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. An exemple of this methodology applied to one particular parameter (cryptosporidium oocyst) has already been presented in reference [2].

This risk assessment method must take into account:

a) The quality parameters of the raw water: the distribution probability of their peaks consecutive to climatic events, pollution...

b) The process line of the treatment plant, namely the successive steps of the treatment process and their types

c) The technology of the different treatment steps, the different possible failure modes and the corresponding failure rates

The risk will be assessed within quantitative indicators (probability for each parameter to exceed the maximal threshold).

These indicators will be synthesized 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.

2. Definition of treatment processes and corresponding transfer functions in nominal mode

The first step of the approach consists of identifying the different types of treatment processes that can be performed in a treatment plant, depending on the raw water quality.

To characterise the water quality (ability for human consumption) more than 60 parameters (physical-chemical, bacteriological...) are defined by the authorities responsible for health 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.

Firstly we have to consider undesirable parameters : turbidity and coloration (that are most visible for the consumer), iron and manganese content, and finally total organic carbon and permanganate value. The former two values allow for supervision of total organic matter content of the water.

Secondly, physical-chemical parameters have to be inspected : dissolved salts, arsenic, fluorides, cyanide, chloride, sulphate, and finally conductivity. It is a global parameter that informs about water mineralization. Higher is the conductivity more the water is mineralized (calcium, magnesium, sulphates, phosphates, chlorides...)
Microbiological parameters are represented by algae, algae's toxins, fecal coliforms, giardia, and cryptosporidium (which could be responsible for gastroenteritis epidemics).

And finally human activity indicators are considered : ammonium, nitrates, hydrocarbons, phenol, pesticides, detergents, and polycyclic aromatic hydrocarbons. The former is a global parameter, including different carbonic compounds suspected to be carcinogenic and that have so to be measured

To take into account these different types of resources, a drinking water treatment plant can be built, with successive treatment steps which can be :

- Pre-oxidation : at the beginning of the treatment, this step permits among others to remove iron, manganese, ammoniac nitrogen, and color. Oxidizing agent could be chlorine, chlorine dioxide, ozone or potassium permanganate.
- Clarification : at this step, suspended solids and colloidal matter (mostly responsible for turbidity) are extracted from raw water by separation of solid and liquid (settling, flotation, filtration). In the case of small particles, it is possible to compete this treatment by precipitation and particle growth treatment (coagulation).
- Polishing : it is essentially adsorption treatment with granular active carbon (GAC) or powdered activated carbon (PAC), which could be associated to ozone oxidation. These step are mainly used to remove dissolved organic micropollutants like pesticides.
- Disinfection : the objective of this step is to remove pathogenic germs, in order to maintain good quality of water in the supply network. Disinfection agents could be chlorine, chlorine dioxide, or ozone. Chloramine or Ultraviolet rays could also be used.
- Specific treatment : for example, iron or manganese removal, denitrifcation or nitrification, aeration. Treatments using membranes could also be used (ultrafiltration, reverse osmosis, nanofiltration), which remove very small particles.

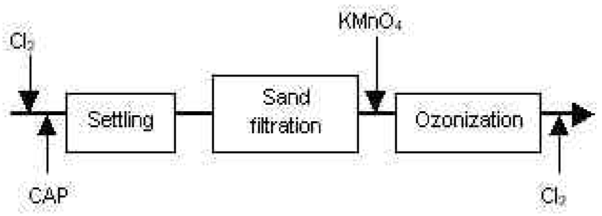


Figure 1 : *exemple of Cholet (France) drinking water production process*

The approach then consists of estimating for each treatment step and for each quality parameter a transfer function. 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 undesirable components that can be introduced in treated water by the treatment step, such as Aluminum salts used as coagulants in settling steps) equivalent to a reduction factor ?, a 100% reduction factor corresponding to the complete elimination of the corresponding component, such as:

$$C_{output} = (1 - r).\ C_{input} \qquad [1]$$

This reduction factor however, can be dependent on the input concentration (the lower the input concentration, the better the treatment step efficiency) inducing non-linearity in 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 (see figure 2). 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.

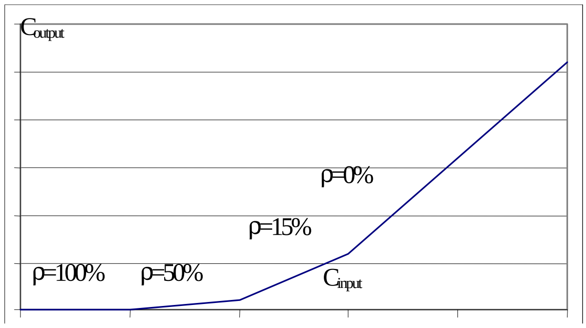


Figure 2 *: approximation of a non linear transfer function*

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, which can only be modified in case of disfuntionnng of a treament step (see following paragraph). This 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 saturated beyond this threshold) rigorous maintenance actions are performed.

3. Failure mode analysis and degraded transfer functions

The second step of the approach consists of determinating 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 of treatment plants, operation and maintenance.
The results of these analyses are synthesized in FMECA arrays as shown in table 1, allowing to clearly identify for each failure mode :

- The possible cause
- The failure rate ? (in hours^{-1}) as known by experience on similar equipments in operation.
- The detection means (immediate detection because the failure strongly affects a quality parameter continuously monitored, detection only during maintenance action…)
- 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 output of the treatment step (qualitative)
- The degraded transfer function for parameters affected by the failure (quantitative) : equivalent to define for the failure mode a degraded reduction factor $?_{degraded}$ smaller or equal to the nominal reduction factor $?_{nominal}$, and which can also depend on the input concentration.

Failure	*Filtration inefficient*
Cause	*Filter saturation*
Failure rate ?(h^{-1})	*Never encountered (1)*
Detection	*Immediate (2)*
Latency T(h)	*Negligible (3)*
Effects	*No filtration effect*
Degraded Transfer Functions	*Turbidity reduction factor becomes 0%*

***Table 1** : An example of a FMECA array*

(1) : With an accurate maintenance policy
(2) : The quality degradation of the produced water is immediately detected by sensors
(3) : The operating instruction recommend to stop the production in that case

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

The detection means and latent period columns allow to determine the corresponding unavailability U=?T (probability to encounter 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 3 illustrates the case of a treatment step becoming completely inefficient consecutively to the failure, like the GAC filtration saturation mentioned above.

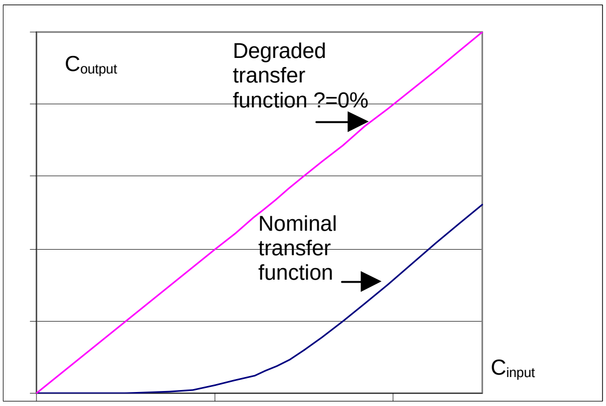


***Figure 3** : An example of transfer function in nominal mode and in degraded mode (failure mode)*

4. 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 (probability that the corresponding concentration exceeds a value as a function of this value). This step involves resource specialists, and must take into account many parameters (climatic, hydrogeological…) 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 :

- Determining the transfer function of the *whole* treatment process obtained by combination of the transfer functions 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.

- Determining the failure conditions of the whole treatment process that have to be taken into account and the corresponding degraded global transfer function. Examination of single failure conditions (one degraded step, the others remaining nominal) is generally sufficient because the combination of two or more failures can in most cases be considered as incredible. This approximation is justified if the single failures are immediately or quickly detected (low latent period and therefore small unavailability values). In cases where this hypothesis would not be valid, it is however possible to determine the failure combinations which must be taken into account, considering that the equivalent unavailability of a two failure combination scenario with respective failure rates and latent periods $?_1$, $?_2$, T_1, T_2 is (if the failures can be considered as independent):

$$U = U_1U_2=\lambda_1\lambda_2T_1T_2 \qquad [2]$$

- Identifying 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 quality standards more constraining.

- Inversing all global transfer functions (nominal and degraded modes), and apply 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 exceeds one of them, a scenario of non-compliant treated water exists. According to what function and what value were used in the calculation of the concerned threshold, this non compliance is relative to health legislation or internal standard and occurs in nominal or degraded mode.

- Estimating 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 (see figure 4).

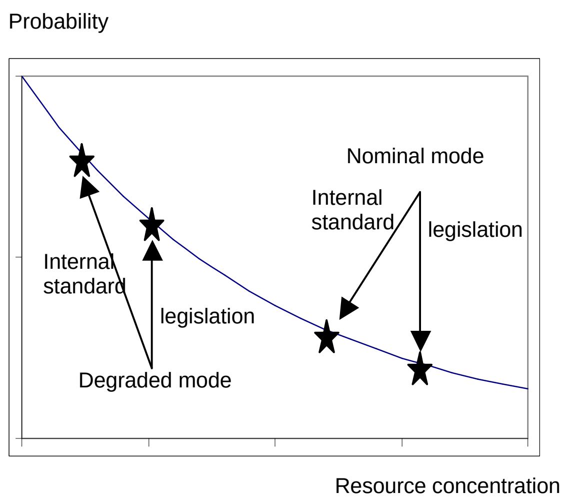


***Figure 4** : an example of a raw water parameter distribution function. In this example two modes for the treatment plant (nominal and degraded) and two types of treated water quality standards (health legislation and internal) are taken into account. If the raw water quality parameter concentration exceeds the value (horizontal axis), the corresponding standard for the*

corresponding mode is not respected. The probability estimation can be read vertically

- In addition to this probabilistic approach, exceptional events (industrial accident, catastrophic flood…), that can affect the resource quality but whose probability is difficult to estimate must be taken into account. The consequences of these events are therefore carefully but separately studied (events/consequences tables without corresponding probability occurrence see table 2).

Event	Consequences	Comment
Catastrophic flood	The river water quality (turbidity and microbiologic aspects) will become too high to be treated by the treatment line of the plant which needs to be stopped	Such an event has never occured in the past century. The well resource quality will remain acceptable and ensure a minimum distribution flow
Toxic product leakage coming from an industry in the vicinity or from a barge on the river	The river can no longer be treated. The plant will be completely stopped	There are no pollutant industries in the vicinity. In case of serious pollution of the river, consumers can be supplied by another treatment plant using another resource.

***Table 2** : an example of an events/consequences table which completes the probabilistic approach by very rare events whose probability is difficult to estimate but whose consequences will be especially serious.*

5. Determination of compliant water availability

The last step of the methodology consists of synthesizing the scenario leading to produce water which does not respect a quality standard, (legal standard or internal standard), and to obtain the corresponding probability (contribution to the global unavailability of compliant water).

For each quality standard a fault tree [3] 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) scenarii events : 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 5 and 6 respectively for internal and legislation standards of the turbidity parameter.

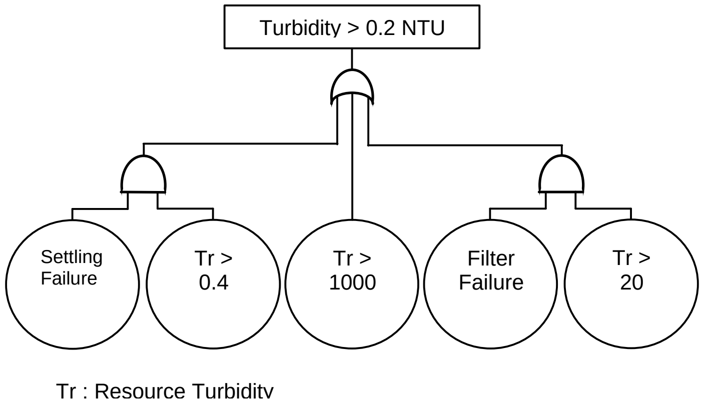


***Figure 5** : An example of a fault tree with a non-compliance to an internal standard as top event*

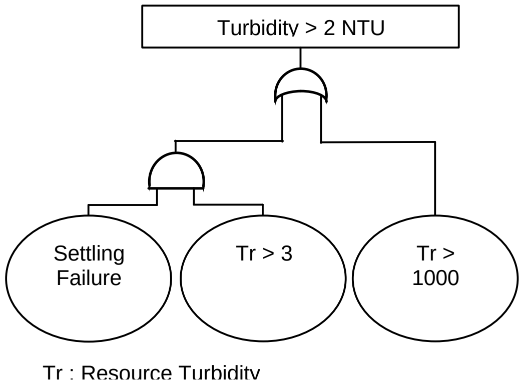


Figure 6 : An example of a fault tree with a non-compliance to a legislation standard as top event

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). The following table shows an example (estimated values, because real values from operations are not yet available) of those elementary events probability :

Event	Probability
Resource turbidity > 1000	$2.7.10^{-4}$ (1day/10 years)
Resource turbidity > 20	0.98
Resource turbidity > 3	0.99
Resource turbidity > 0.4	1
Filtration unavailability	0.01
Settling unavailability	$2.7.10^{-3}$ (1day/ years)

***Table 3 :** probabilities of elementary events*

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

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

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

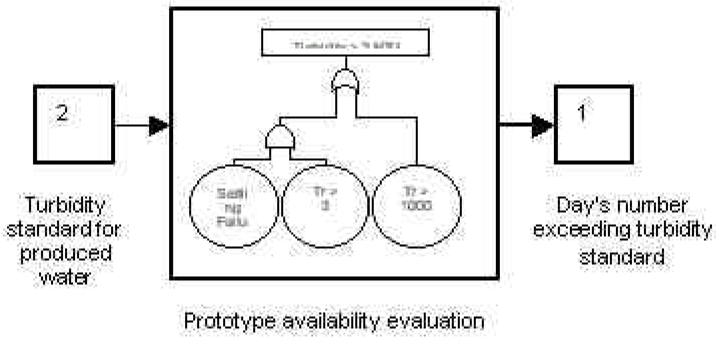


***Figure 7**: After treatment plant modelization (see hereafter), the tool is able to determine the number of days exceeding a given produced water standard.*

6. Software tool and application

This approach, integrating a water treatment plant simulator, has been implemented, and a software tool prototype has been developed (figure 7). The design of the treatment process, optimizing risk regarding cost, becomes easy. The user can choose treatment boxes in order to construct different technical options for a process line and then evaluate the risk of non-compliant produced water.

Concretely, this tool enables the choice of the treatment line regarding the different categories (Pre-oxidation, Clarification, Polishing, Disinfection, Specific treatment…) by selecting the specific treatment box (chlorination, settling, ultrafiltration, iron removal…). These boxes have two inputs: a) reactive dosage: Cl_2, O_3, ClO_2, $KMnO_4$, O_3/H_2O_2… b) Concentration of quality parameters coming from the output of the previous box.

Plant modelization must be done from left (raw water) to right (drinking water), and must follow the treatments as they are ordered in the drinking water treatment plant. Arrows linking different boxes, are in the other way, from right (treated water) to left (raw water). They represent the methodology calculating thresholds of each parameter from the end to the beginning of the plant, using transfer functions. Inputs of this modelization correspond also to outputs for the real production process, as shown in the example of Cholet plant (France) (figure 9).

On the final output, we have thresholds relative to raw water quality :
if the resource quality parameters exceed one of them, a scenario of non-compliant treated water exists.

A screen copy of the simulator shows the interface where treatment plant can be described using treatment boxes contained in the library (see figure 8), and an exemple of one plant (see figure 9). On figure 10, we can see a parameters display corresponding to acceptable thresolds, calculated by application of French normalization to plant exposed on figure 9.

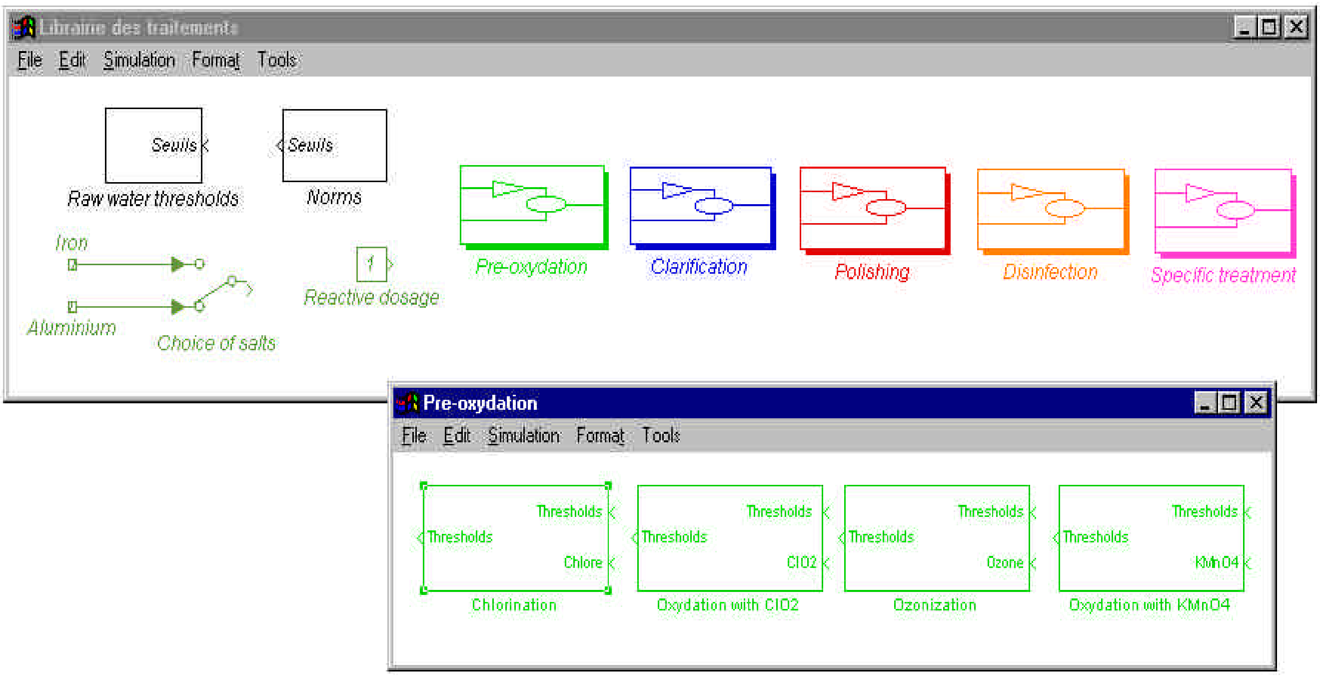


***Figure 8** : Treatment library of the simulator*

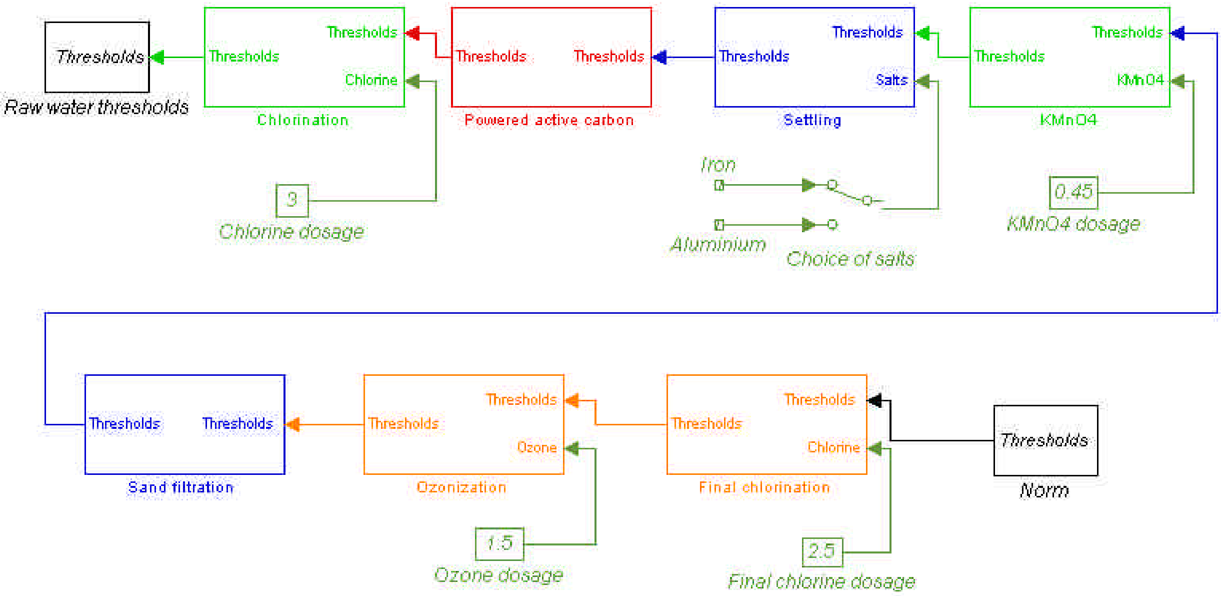
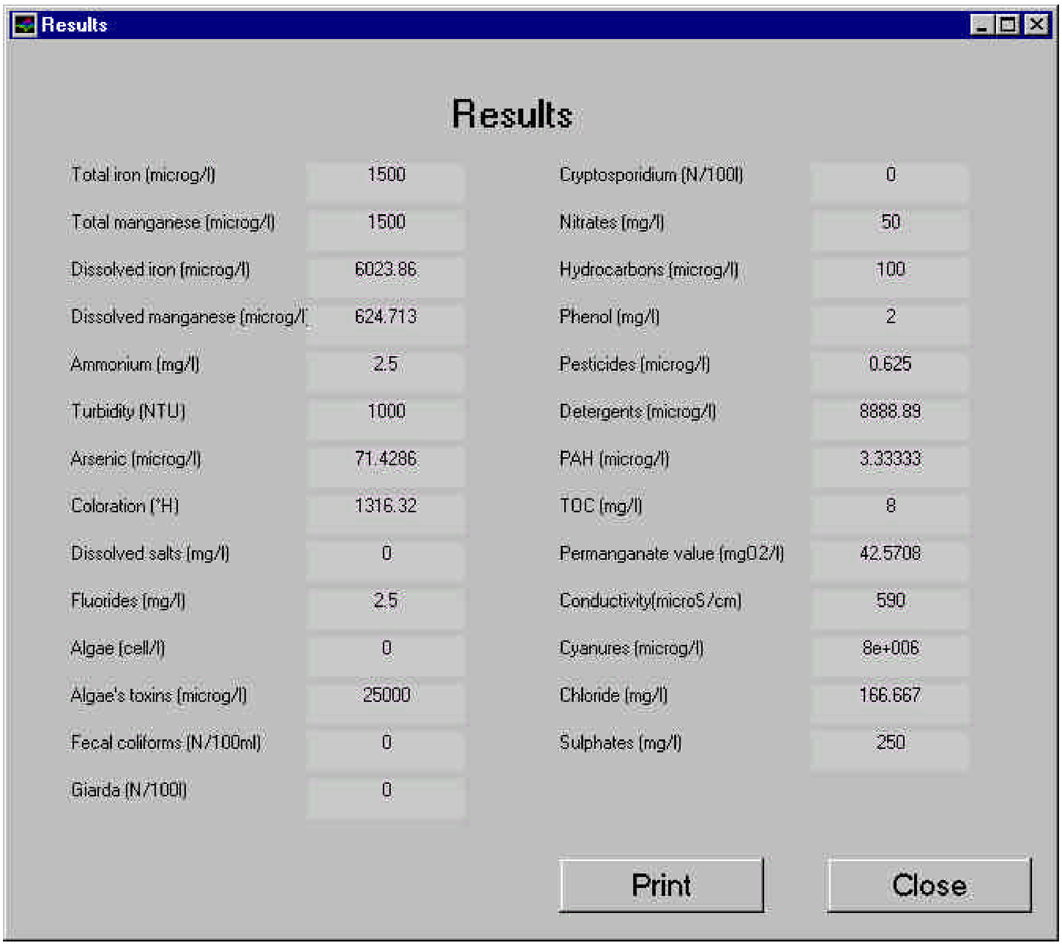


Figure 9 *: Exemple of plant defined by the simulator*



Results

Results

Total iron (microg/l)	1500	Cryptosporidium (N/100l)	0
Total manganese (microg/l)	1500	Nitrates (mg/l)	50
Dissolved iron (microg/l)	6023.86	Hydrocarbons (microg/l)	100
Dissolved manganese (microg/l	624.713	Phenol (mg/l)	2
Ammonium (mg/l)	2.5	Pesticides (microg/l)	0.625
Turbidity (NTU)	1000	Detergents (microg/l)	8888.89
Arsenic (microg/l)	71.4286	PAH (microg/l)	3.33333
Coloration (°H)	1316.32	TOC (mg/l)	8
Dissolved salts (mg/l)	0	Permanganate value (mgO2/l)	42.5708
Fluorides (mg/l)	2.5	Conductivity(microS/cm)	590
Algae (cell/l)	0	Cyanures (microg/l)	8e+006
Algae's toxins (microg/l)	25000	Chloride (mg/l)	166.667
Fecal coliforms (N/100ml)	0	Sulphates (mg/l)	250
Giarda (N/100l)	0		

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Figure 10 *: Parameters displays*

7. Conclusion

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

We presented a specific approach consisting of defining transfer functions for each treatment step and each quality parameter (in nominal and all degraded modes) and invert the global transfer function to determine the raw water quality thresholds which must be respected to produce compliant water. Scenarii of compliant water unavailability are then analyzed using fault trees. The generation and the quantification of the fault tree has been packaged in a prototype; user design his process line by choosing the appropriate treatment boxes (coloration, settling, ultrafiltration, iron removal…) and the dosage of reactives.

This approach will be applied on calls for bids at the International Project Department. It will be important to have return on experience of the use of this approach regarding the classical one where experts evaluate by experience of the risk.

8. References

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