Comparing risk-reduction measures to reach water safety targets using an integrated fault tree model

L. Rosén, A. Lindhe, O. Bergstedt, T. Norberg and T. J. R. Pettersson

ABSTRACT

In the third edition of the *Guidelines for Drinking-water Quality*, the World Health Organization concludes that an integrated management of risks in source waters, treatment systems and distribution networks is the most effective way to guarantee safe drinking water to consumers. The integrated approach is fundamental to avoid sub-optimisation of risk-reduction measures. This paper presents an application of an integrated and quantitative risk model for comparing risk-reduction measures to support decisions for reaching specified water safety targets. A fault tree approach is used for structuring the risk analysis and for estimating the risk, expressed as Customer Minutes Lost (CML). Input information is a combination of hard data and expert judgements. Uncertainties in input information are considerable and modelled by a Bayesian statistical approach. A drinking water system in Sweden is used to exemplify model application. Quantitative safety targets have been confirmed at the political level as a basis for long-term planning of investments and reinvestments. One target defines an acceptable risk level of 144 annual CML for the average consumer. For the current system structure an estimated risk of 612 CML was obtained. Four risk-reduction alternatives were compared and they reduce the risk to between 50 and 81 CML, i.e. below the acceptable level. The paper describes how a structured and thorough analysis of risk-reduction measures can facilitate transparency and long-term planning of drinking water systems.

Key words | decision support, fault tree, risk assessment, risk reduction, uncertainty, water safety plan

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INTRODUCTION

The World Health Organization (WHO 2008) concludes that end-product testing in treatment and distribution systems is not sufficient to guarantee safe drinking water to consumers. To ensure safe drinking water a holistic risk management approach from catchment to consumer is emphasised. The *Framework for Safe Drinking Water* presented by Davison *et al.* (2005), and included in the WHO guidelines (WHO 2008), comprises the preparation of Water Safety Plans (WSPs) in which risks in source waters, treatment systems and distribution networks should be assessed and managed (see also Bartram *et al.* 2009). WSPs are currently being implemented in several countries and are expected to become an increasingly important part of water management in both developed and developing countries. The Bonn Charter strategy presented by the International Water Association (IWA 2004), further specifies the use of WSP in drinking water management. The guidelines on WSPs provide general descriptions of hazard identification and a method for qualitative (or semi-quantitative) classification of risks. The method provides a useful structure for risk assessment and facilitates a ranking of risks as a basis for prioritising safety measures. Qualitative methods for risk ranking are commonly used in many disciplines, e.g. engineering, mining, environmental and

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industrial management. It relies on qualitative, often subjective, estimates of probabilities and consequences. The result is often presented using a risk matrix. Favourable aspects of the approach are that it is easy to use, provides transparency and facilitates a basis for communication between stakeholders. A major drawback of risk ranking methods is that it is difficult to properly model complex systems with interactions between components. This may cause suboptimal prioritisation of risk-reduction measures and an inefficient use of available resources. Furthermore, risk ranking methods assume a discrete nature of hazards, cannot provide quantitative estimates that can be directly compared to performance targets, and typically lack procedures for sensitivity and uncertainty analysis (Burgman 2005).

Drinking water systems are often complex with numerous components that interact in various ways. In this paper, a fault tree model is used to properly account for different types of interactions between system components and to include the entire drinking water system, from source to tap. The approach allows for two very important types of assessments in risk management: (1) quantitative comparison to established water safety targets; and (2) evaluation of the efficiency of risk-reduction measures. The fault tree model considers quantity as well as quality failures and is described in detail by Norberg *et al.* (2008) and Lindhe *et al.* (2009*b*). The results presented in this paper has also been presented in a conference paper by Lindhe *et al.* (2009*a*). Further application of the fault tree model in combination with an economic analysis is presented by Lindhe *et al.* (*In preparation*).

The purpose of this paper is to illustrate and evaluate the use of the fault tree model for comparing four alternative risk-reduction measures for the Gothenburg drinking water system in Sweden. Water safety targets have been quantified and confirmed at the political level as a basis for the long-term planning of investments and reinvestments. The targets consider events such as waterborne disease and major delivery failures. A previous risk analysis of raw water availability showed high probability of interruption in the supply to one of the two treatment plants due to failures in the raw water transfer system (Rosén & Steier 2006). Previous applications of the fault tree model at the Gothenburg system showed that failures related to the raw water system contribute most to the total risk level, expressed as Customer Minutes Lost (Lindhe *et al.* 2009*b*). The maximum capacity of each plant is far below the average need and drinking water storage is well below the daily need. An additional analysis of the dominating failure scenario showed that increased treatment capacity would reduce the risk of extensive delivery interruptions to an acceptable level, and that the raw water supply would not be a limiting factor in this scenario. As a result, increased treatment capacity has been discussed as a possible risk-reduction measure. However, there are other events, including pollution of the raw water reservoir, where additional raw water sources would be crucial for facilitating sufficient drinking water production. Several alternative options for additional raw water sources have been identified and there is a need of quantifying their contribution towards meeting the established safety targets.

Four alternative risk-reduction measures are analysed in this paper: (1) increase of water treatment capacity; (2) increased treatment capacity combined with regulation of smaller lakes; (3) increased treatment capacity combined with regulation of larger lake; and (4) a combination of alternatives (2) and (3). The total risk for each of the four alternative measures is calculated and compared to the risk level for the present day situation.

THE GOTHENBURG DRINKING WATER SYSTEM

Gothenburg is the second largest city in Sweden and approximately 500,000 consumers are supplied with drinking water. The system is based solely on surface water and the main raw water source is the river Göta Älv, a moderately polluted river (e.g. Westrell *et al.* 2003). A schematic description of the Gothenburg raw water system, including possible alternative raw water sources, is given in Figure 1. Two smaller lakes (*main reservoir lakes* in Figure 1) are used for intermediate storage of water and to improve the water quality. Approximately half of the water taken from the river is transferred directly to *treatment plant no 1*. The other half is transferred via a 12 kilometres rock tunnel to the main reservoir lakes. From the main reservoir lakes water is pumped to *treatment plant no 2*.

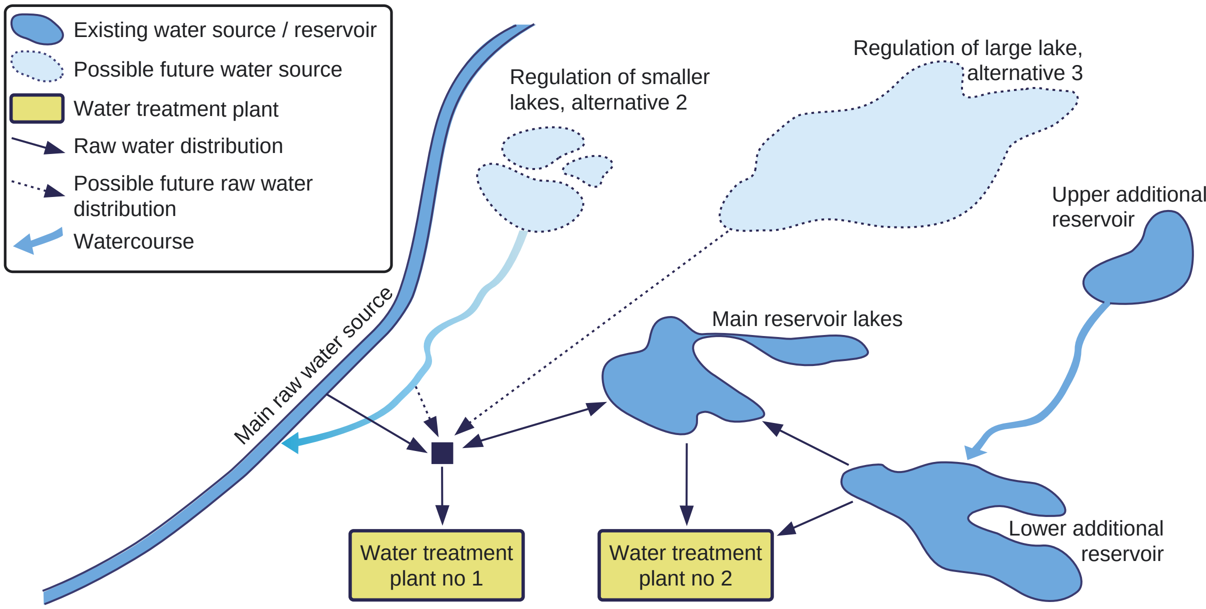

Figure 1 | Schematic description of the Gothenburg raw water system. Possible future raw water supplies included in the analysis are further described in the *Risk-reduction alternatives* section.

Due to the variable quality of the river water, the intake is closed 100 days a year on average (e.g. Åström *et al.* 2007; Åström *et al.* 2009). Decisions to close the intake are based on online monitoring and reports from operating bodies upstream, e.g. municipalities and industries. Typical parameters monitored online are, turbidity, conductivity, redox-potential and pH. In addition, microbiological analyses are regularly carried out.

When the intake from the main water source is closed, the main reservoir lakes supply both treatment plants. During periods of closure of the intake, water from a reservoir in an additional raw water supply system (*lower additional reservoir* in Figure 1) can be pumped to the main reservoir lakes or directly to treatment plant no 2. However, the situation where treatment plant no 1 has no alternative raw water supply of its own makes the system vulnerable. The treatment plants have approximately the same production capacity and similar treatment processes, including chemical flocculation, sedimentation, filtration and disinfection. Online measurements and laboratory analyses are used to monitor the water quality at the treatment plants. Both treatment plants contribute in approximately equal parts to meet an average drinking water demand of 165,000 m^3/d. Normally the water demand varies between 120,000 and 210,000 m^3/d. The maximum treatment capacity is 150,000 m^3/d for treatment plant no 1 and 120,000 m^3/d for treatment plant no 2. Treatment capacities are normally lower than the maximum due to maintenance work. The distribution network is approximately 1,700 km in length. To ensure sufficient pressure in elevated supply zones, the water head is raised through 66 booster stations and 14 service reservoirs are used to meet peaks in the water demand. Monitoring of the water quality in the distribution system is made at different locations, e.g. in private taps and pumping stations.

METHOD

Conceptual model

The overall failure event in the model is supply failure, including: (1) quantity failure, i.e. no water is delivered to the consumer; and (2) quality failure, i.e. water is delivered but it does not comply with existing quality standards. In Figure 2 the two categories of failure and their main causes are illustrated. Quantity failure may occur due to failure of components, e.g. pumps and pipes, or because the water utility decides to stop the delivery when an unacceptable

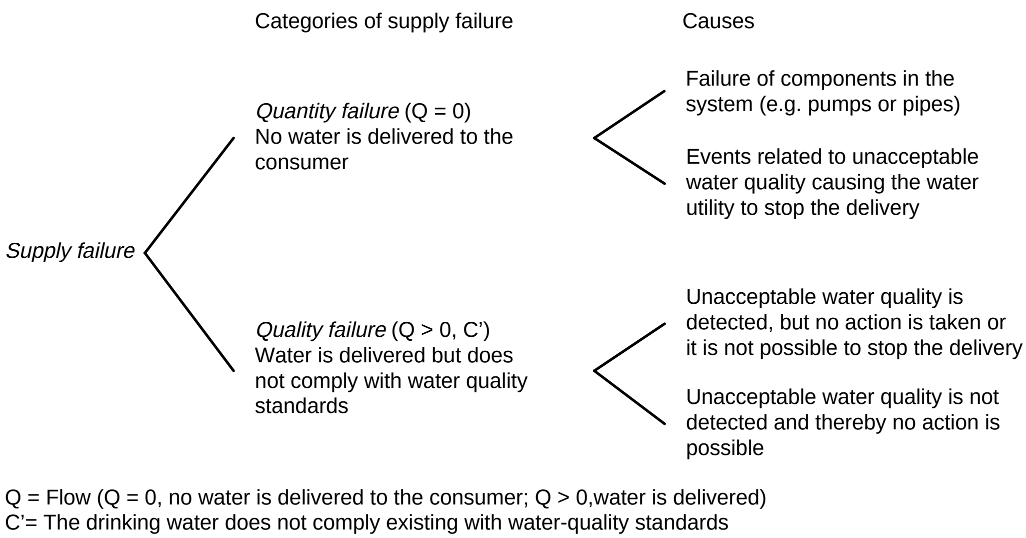

Figure 2 | Categories of supply failure and their main causes (Lindhe *et al.*, 2009*b*).

water quality has been detected. Quality failure may occur when an unacceptable water quality is not detected or when it is detected, but no action is taken. Events that may cause an unacceptable water quality are, for example, chemical or microbial discharge to the water source, failure of treatment processes or pipe bursts. The drinking water was considered unacceptable when unfit for human consumption based on the Swedish national quality standards for drinking water (SLVFS 2001:30). Although the applied model can be used to analyse both quantity and quality failures, only the previous is considered when comparing the risk-reduction measures studied in this paper.

The drinking-water system was modelled as a supply chain composed of three sub-systems: raw water source, treatment system and distribution network. Events in any of the sub-systems may cause supply failure, but the sub-systems are also capable of compensating for failure. For example, if one treatment plant fails to produce drinking water, reservoirs in the distribution system and increased production at the other treatment plant may prevent quantity failure. However, the ability to compensate is limited in time, because the reservoir volume is limited. Another example is when raw water that does not meet set-up raw water quality criteria is used, and the treatment still is able to produce water that complies with the drinking water quality standards.

The fault tree model

The fault tree model for integrated risk analysis of drinking-water systems is described in detail by Norberg *et al.* (2008) and Lindhe *et al.* (2009*b*). A fault tree analysis is a structured process that identifies potential causes of system failure (Bedford & Cooke 2001). A fault tree represents interactions between different events by logic gates, and shows how the events may lead to system failure, i.e. the *top event*. The two most common types of logic gates are the OR- and AND-gates, which are used in the present model. Starting with the top event, the tree is developed until a required level of detail is reached. Initiating events are denoted *basic events* and logical combinations of these are denoted *intermediate events*. The top event represents failure of the system while basic events represent failures of components. The capability of representing interactions between critical system components makes fault tree models powerful for analysis of entire drinking water systems. A recent example of a more holistic application of fault trees concerning waterborne outbreaks is presented by Risebro *et al.* (2007). A schematic fault tree model illustrating the main type of events included in the analysis of the Gothenburg system is shown in Figure 3. The full model includes approximately 100 basic events.

A Markovian approach is used with variables failure rate λ and mean downtime $1/\mu$. The mean time to failure

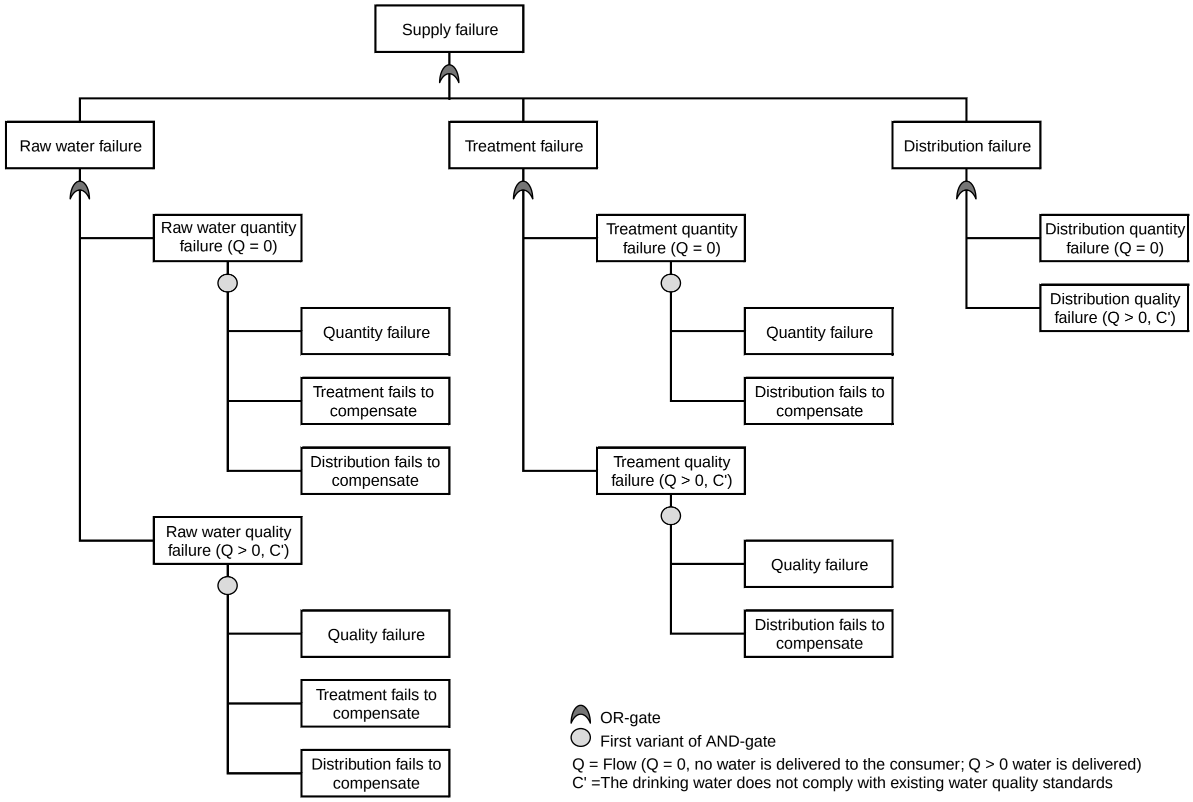

Figure 3 | Schematic fault tree including the main type of events.

(uptime) is $1/\lambda$, hence the probability of failure is $P_F = \lambda/\lambda + \mu$). The main reasons for using the failure rate and mean downtimes instead of direct estimations of probability of failure, is to facilitate relevant elicitation of expert judgements and modelling of the dynamic behaviour of the system. Using uptimes and downtimes of basic events makes it possible to estimate the duration of failures and the time intervals to failures for all events in the fault tree. The fault tree of the Gothenburg system was constructed using four types of logic gates: OR-gates, AND-gates and two new variants of the AND-gate. The OR-gate describes a series system where only one input events has to occur to cause the system to fail. The AND-gate describes a parallel system where all input events have to occur to cause the system to fail. To be able to consider the inherent ability of a system to compensate for failure, Norberg *et al.* (2008) and Lindhe *et al.* (2009*b*) formulated two additional variants to the common type AND-gate. The first variant describes a situation where failure of one component may be compensated for by one or several other components during a limited time period. The second variant represents a situation where a compensating component that has failed may recover and start to compensate again. Equations for calculating the probability of failure, the failure rate and mean downtime at each intermediate level of the fault tree, are given in Table 1. Here, q_i denotes the *probability of failure on demand* where a compensating component *i* fails to start compensating when needed, e.g. a reserve pump that cannot be started when the main pump brakes down. Failure during operation is the other type of failure and is represented by the failure rate; e.g. the reserve pump starts, but after some time it too brakes down.

Customer minutes lost (CML) and risk

The risk (R) was estimated in terms of Customer Minutes Lost (CML). Risk was defined as the expected value of CML. Using the applied fault tree model, CML values for

Table 1 | Equations used to calculate the output of the logic gates (Norberg *et al.* 2008; Lindhe *et al.* 2009*b*). Variable P_F is the probability of failure, λ_i the mean failure rates, μ_i the mean repair rates ($1/\mu_i$ the mean downtimes) and q_i the probabilities of failure on demand. For the variants of the AND-gate $i = 1$ corresponds to the failure that may be compensated for by events $i = 2, \ldots, n$

OR-gate	AND-gate
$\lambda = \sum_{i=1}^{n} \lambda_i$	$\mu = \sum_{i=1}^{n} \mu_i$
$\mu = \sum_{i=1}^{n} \lambda_i \cdot \frac{\prod_{i=1}^{n} \mu_i}{\prod_{i=1}^{n} (\lambda_i+\mu_i) - \prod_{i=1}^{n} \mu_i}$	$\lambda = \sum_{i=1}^{n} \mu_i \cdot \frac{\prod_{i=1}^{n} \lambda_i}{\prod_{i=1}^{n} (\lambda_i+\mu_i) - \prod_{i=1}^{n} \lambda_i}$
$P_F = \frac{\lambda}{\lambda+\mu} = 1 - \prod_{i=1}^{n} \frac{\mu_i}{\lambda_i+\mu_i}$	$P_F = \frac{\lambda}{\lambda+\mu} = \prod_{i=1}^{n} \frac{\lambda_i}{\lambda_i+\mu_i}$
1st variant of AND-gate	*2nd variant of AND-gate*
$\mu = \mu_1$	$P_F = \frac{\lambda_1}{\lambda_1+\mu_1} \cdot \frac{\lambda_2+q_2(\mu_1+\mu_2)}{\lambda_2+\mu_1+\mu_2}$
$P_F = \frac{\lambda_1}{\lambda_1+\mu_1} \cdot \prod_{i=2}^{n} \frac{\lambda_i+q_i\mu_1}{\lambda_i+\mu_1}$	$\lambda = \frac{\mu_1\lambda_1 q_2(\lambda_2+\mu_1+\mu_2)+\lambda_1\lambda_2(1-q_2)(\mu_1+\mu_2)}{(\lambda_1+\mu_1)(\lambda_2+\mu_1+\mu_2)(1-P_F)}$
$\lambda = \frac{P_F}{1-P_F} \cdot \mu$	$\mu = \frac{\mu_1\lambda_1 q_2(\lambda_2+\mu_1+\mu_2)+\lambda_1\lambda_2(1-q_2)(\mu_1+\mu_2)}{(\lambda_1+\mu_1)(\lambda_2+\mu_1+\mu_2)P_F}$

both quantity and quality failures can be calculated. In order to retain transparency these two types of risks should always be presented separately. Since this study is only considered with quantity failures, all CML values refer to quantity failures and are equivalent to the number of minutes per year the average consumer is not supplied with drinking water. The quality-related CML values relate to the number of minutes per year the average consumer is supplied with water that does not meet the quality standards. The quality-related CML values could also be named Substandard Supply Minutes. A comprehensive description of the term CML is presented by Lindhe *et al.* (2009*b*). Blokker *et al.* (2005) describes the use of CML as a performance indicator in the Netherlands. To consider that the system may not fail when in failure mode, it can be shown that the expected value of CML should be calculated as $R = P_F \cdot C$, where P_F is the probability of failure and C is the proportion of all consumers affected (Lindhe *et al.* 2009*b*). Since the top event in the fault tree, supply failure, is a combination of different types of events, the proportion of consumers affected (C) cannot in a meaningful way be defined for the top event. Instead, C was defined at a lower level in the fault tree for n different events. The total risk was thus calculated as

$$R = \sum_{i=1}^{n} P_{Fi} C_i$$

Uncertainty analysis

To enable uncertainty analysis all input parameters were expressed as probability density functions and the calculations were performed by Monte Carlo simulations (10,000 iterations). The parameters λ and μ are exponential rates and were modelled by Gamma distributions. The proportion of the consumers affected (C) and the probability of failure on demand (q) were modelled by Beta distributions. These distributions facilitate a Bayesian approach, where new information, e.g. monitoring data, can be used for a mathematically formal updating of previous knowledge. The Monte Carlo simulations facilitate two important types of analyses: (1) sensitivity analysis of contributions to the

Table 2 | Change in input variables for risk-reduction alternatives

Alternative	Major changes in input variables of the fault tree model
0. No measures taken	–
1. Increased treatment capacity	Based on statistical data on water demand and estimations regarding the reliability of the treatment plants, the time for compensation (uptime) was estimated to be between 3–120 days (90%-interval) and the probability of failure on demand 0.0025–0.01 (90%-interval)
2. Increased treatment capacity combined with regulation and supply from smaller lakes	If available and if only treatment plant no 1 needs supply, the source is available (uptime) 25–35 days (90%-interval), whereas if both treatment plants need to be supplied the available time (uptime) is restricted to 8–18 days (90%-interval). When the lakes are not available, the duration (downtime) is 7–60 days (90%-interval)
3. Increased treatment capacity combined with regulation and supply from larger lake	The time to failure (uptime) is 5–15 (90%-interval) for all three events considered (water shortage, failures in the transfer of raw water and unacceptable water quality in the lake). When failure occurs the duration (downtime) is estimated to be 1–30 days for water shortage, 0.5–2 days for transfer failures, and 5–30 days for water quality failures (all 90%-interval)
4. Combination of alt. 2 and 3	See alternatives 2 and 3

total uncertainty from uncertainties in basic events; and (2) analysis of the probability of not meeting established safety targets for the water supply.

Water safety targets in Gothenburg

The City of Gothenburg has prepared an action plan which includes performance targets regarding the supply of drinking water (Göteborg 2006). These targets are politically established and can be considered as acceptable levels of risk. The performance target used in this analysis is Duration of interruption in delivery to the average consumer shall, irrespective of the reason, be less than a total of 10 days in 100 years'. For the average consumer this translates to an acceptable risk level of 144 annual CML.

RISK-REDUCTION ALTERNATIVES

The following four alternative risk-reduction measures were analysed: (1) increased treatment capacity in the two treatment plants, the increase will make each of the plants capable of producing up to the average total drinking water demand; (2) increased treatment capacity combined with increase in regulation of some fairly pristine lakes to

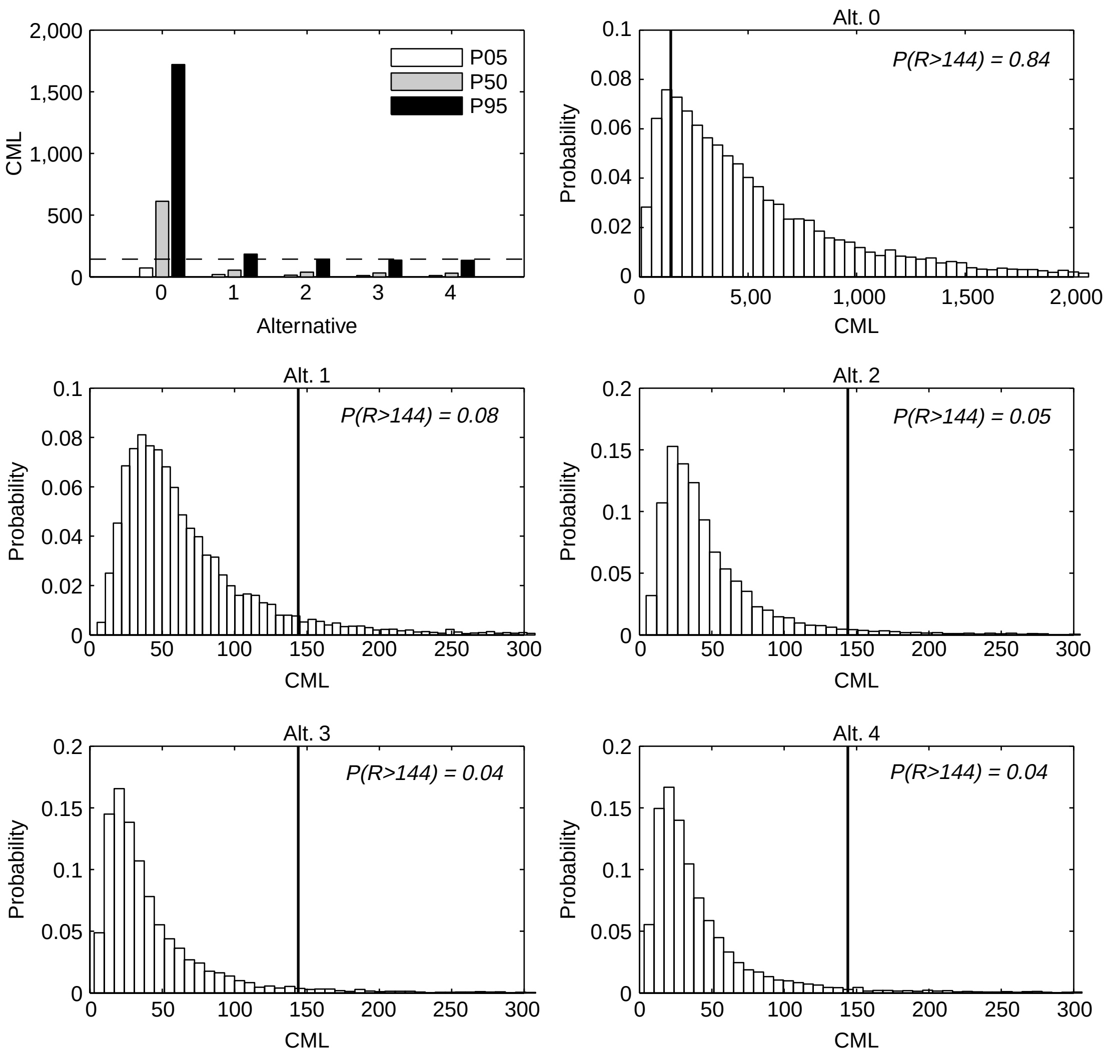

Figure 4 | Histogram showing 5-, 50- and 95-percentiles of simulated risk values for the risk-reduction measures (upper left). Acceptable risk level (144 annual CML) indicated by dashed horizontal line. Uncertainty distributions of risk values expressed as E(CML) for each risk-reduction measure. Acceptable risk level (144 annual CML) indicated by solid vertical lines. The probability of exceeding 144 CML, $P(R > 144)$, is presented for each alternative.

increase the flow in a river for transfer to the drinking water system, these lakes contain relatively large raw water volumes but their watershed is too small for a continuous supply; (3) increased treatment capacity combined with change of regulation of the largest lake and watershed in the area and construction of a pipeline for raw water transfer to the drinking water system, this lake has almost no restrictions in water availability but failures may occur due to dry periods causing water shortage, problems in the transfer of raw water from the lake to the treatment plant or due to pollution events; and (4) combination of alternatives (2) and (3), i.e. increased treatment capacity in combined with regulation of both the smaller lakes and the larger lake. The alternative raw water supplies (in alternatives 2 and 3) are illustrated in Figure 1 and changes in input variables of the fault tree model are described for each alternative in Table 2.

RESULTS

The results from the simulations are presented in Figure 4. It can be seen that before any risk-reduction measures have been taken (alt. 0) the acceptable risk level (144 CML) is clearly exceeded for the average consumer (mean value 612 CML). The probability of exceeding the acceptable level is 0.84. When increasing the treatment capacity in the plants (alt. 1), the mean value for the risk is below the acceptable risk level (81 CML). Due to the uncertainties of input values in the model, the probability of exceeding the acceptable risk level is 0.08. Adding regulation of the smaller lakes to the increased treatment capacity (alt. 2) results in further reduction of the mean risk value to 59 CML and the probability of exceeding the acceptable level to 0.05. When increased treatment capacity is combined with regulation of the larger lake (alt. 3), a mean risk level of 52 CML is obtained. The probability of exceeding the acceptable risk level is 0.04 for this alternative. There is no dramatic difference between the resulting risk levels of alternatives 2 and 3. Combining alternatives 2 and 3 will of course provide the greatest risk reduction (mean value 50 CML), but compared to alternatives 2 and 3 the reduction is not substantially lower. The probability of exceeding the acceptable risk level is 0.04 for alternative 4.

Increased treatment capacity has a large effect on the risk level. After the treatment capacity has been increased additional water sources can no longer provide any large additional risk reduction. The reason for this is that after the treatment capacity has been increased the raw water part is no longer the dominating contributor to the total risk level. Thus, after increasing the treatment capacity, the treatment and distribution systems become relatively more important contributors to the total risk level and need to be considered to further reduce the risk. Another effect is that although the larger lake is a more reliable water source compared to the smaller lakes, regulation of the larger lake cannot provide a substantial risk reduction after implementation of the increased treatment capacity.

CONCLUSIONS

The comparison of the risk-reduction alternatives shows that the increased treatment capacity provides a substantial risk reduction. An important aspect when evaluating the results is to consider what level of certainty that should be required for not exceeding the acceptable risk level. This criterion has to be defined by the decision-makers and it determines what alternatives may be accepted. If, for example, a certainty criterion of 0.05 is used (i.e. the probability of having a risk level above 144 CML should not exceed 0.05), increased treatment capacity (alt. 1) is not enough to meet the criterion. A certainty criterion of 0.05 is often applied when considering uncertainties in risk evaluations, although other criteria may of course be used. If a certainty criterion of 0.05 is used, the smaller lakes (alt. 2), the larger lake (alt. 3) or both have to be included in the system (alt. 4). Since the results of this analysis does not show any significant difference between alternatives 2, 3 and 4 it seems most reasonable to select alternative 2 or 3. However, the alternatives may have other benefits and effects, not included in this analysis. Examples of other important aspects to consider when making decisions are the time it takes to implement the measures, possible effect on the quality-related risk and the cost of each measure. The results presented in this paper are being further analysed by the authors and additional studies are in progress to also include the economic aspects of alternatives (Lindhe *et al. In preparation*).

The application of the fault tree model illustrates its possibilities as a decision support tool for structured comparison of alternative risk-reduction measures. The risk reduction of alternatives that influence different parts and components of a system can be quantified, taking into consideration the interactions between system components. In this study, alternative measures related to the treatment capacity and possible future water sources were compared, but also measures within the distribution system can be analysed. The model facilitates two very important analyses for decision support in risk management: (1) analysis of the risk reduction provided by a specific action; and (2) analysis of the uncertainty of the risk estimate, which enables an estimation of the probability of not reaching established acceptable risk levels. Furthermore, the model provides transparency and a basis for long-term planning of drinking water systems.

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