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Risk assessment case study

Göteborg, Sweden

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Risk assessment case study – Göteborg, Sweden

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Summary

Within Work Area 4 (WA4) *Risk Assessment and Risk Management*, in the TECHNEAU project, six risk assessment case studies were carried out at different drinking water systems during 2007-2008. This report presents a risk assessment of the drinking water system in Göteborg, Sweden. The assessment was carried out using an integrated and probabilistic fault tree method. The main purposes of the case study were to assess the specific drinking water system and evaluate the applied fault tree method.

The Göteborg system was analysed by means of an integrated and probabilistic fault tree analysis. The integrated approach means that the entire system, from source to tap, was included in the analysis. Uncertainties in input variables as well as in the results were considered. The overall failure event studied in the analysis was *supply failure*. This failure may arise due to: (1) *quantity failure*, i.e. no water is delivered to the consumer; or (2) *quality failure*, i.e. water is delivered but does not comply with existing water quality standards. The risk was expressed as the expected value of Customer Minutes Lost (CML). In addition to risk levels, the analysis provided information on probabilities of failure, failure rates and durations of failure. The results were presented separately for quantity and quality failures to retain transparency. Hard data (e.g. measurements and statistics on events), expert judgements and combinations of these were used to estimate required input variables. The calculations were performed by means of Monte Carlo simulations.

The results show that the raw water system contributes most to the total risk levels (expressed as CML) related to both quantity and quality failures. Failures occur most frequently in the distribution system. However, as few consumers are affected and the mean downtime is short, distribution failures have a small influence on the total risk level. The results were compared to politically established performance targets regarding the reliability of the supply. It was shown that the probability of exceeding the analysed performance targets is high.

The applied method enables integrated risk analysis and provides information on risk levels as well as the dynamic behaviour of the system (i.e. probabilities of failure, failure rates and downtimes). It is also possible to estimate the probability of exceeding acceptable levels of risk or other criteria. Furthermore, risk reduction options can be modelled and evaluated using the fault tree. By comparing the different sub-systems contribution to the risk and evaluate the efficiency of different risk reduction options, sub-optimisation of options can be minimised. Hence, the method facilitates discussions on risks to the system and system function.

Contents

1 Introduction

1.1 Background

Within Work Area 4 (WA4) *Risk Assessment and Risk Management*, in the TECHNEAU project, six risk assessment case studies were carried out at different drinking water systems during 2007-2008. The aim of the case studies was to apply and evaluate the applicability of different methods for risk analysis (i.e. hazard identification and risk estimation) and to some extent risk evaluation of drinking water supplies, see Figure 1. The case studies provide six examples where different methods have been applied to demonstrate how risks in drinking water systems can be analysed and evaluated. The drinking water supplies in the following six locations constitute the case study sites where risk assessments were performed in WA4:

a) Göteborg, Sweden
b) Bergen, Norway
c) Amsterdam, the Netherlands
d) Freiburg-Ebnet, Germany
e) Březnice, Czech republic
f) Upper Mnyameni, Eastern Cape, South Africa

The present report presents a risk assessment of the drinking water system in Göteborg (a), Sweden, carried out using an integrated and probabilistic fault tree method. This case study was conducted by Chalmers University of Technology in collaboration with Göteborg Vatten, which is the local water utility.

Göteborg Vatten supplies approximately 500,000 people with drinking water by means of a complex raw-water supply system, two treatment plants and a distribution system of approximately 1,700 km in length. One of the main goals stated by the City of Göteborg is to make sure that all citizens have a reliable access to healthy drinking water, based on a sustainable supply system. In order to provide this, an efficient risk management is of primary importance. The City of Göteborg is constantly identifying and analysing risks that potentially may cause harm to the supply system and consumers. This risk assessment aims to evaluate the applied method and provide knowledge on risks, how they may affect the supply system and how the reliability and safety may be enhanced.

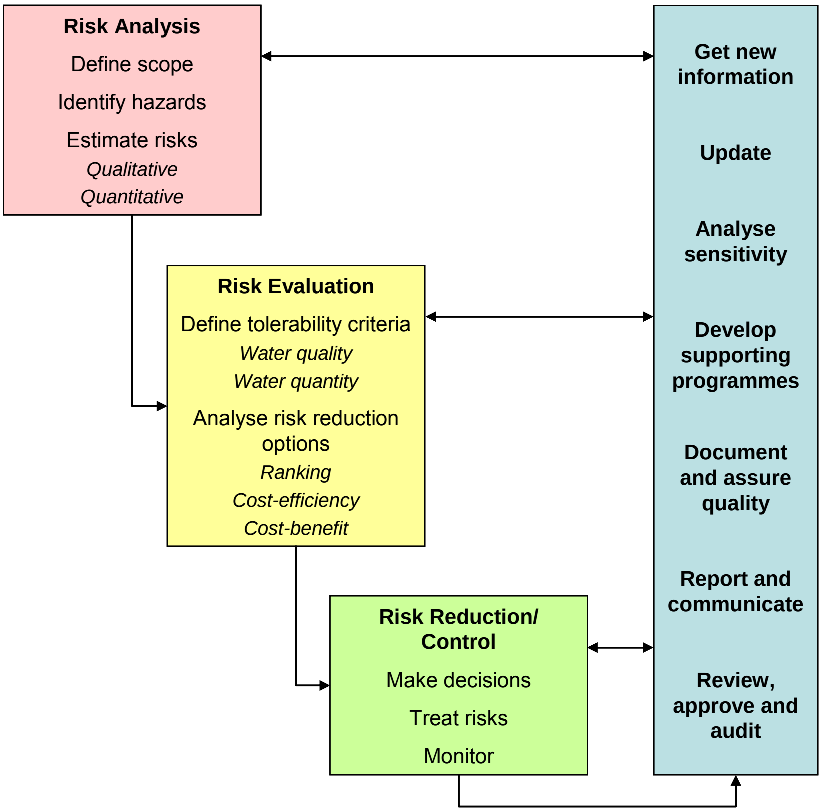

Figure 1. Main components of the TECHNEAU generic framework for integrated risk management in water safety plans (Rosén et al., 2007).

1.2 Objectives and scope

The risk assessment presented in this report is based on a method for integrated and probabilistic fault tree analysis (see Section 1.3). The entire drinking water system is included in the analysis and failures related to the ability to deliver water to the consumers (quantity failure) as well as failures related to the water quality itself (quality failure) are considered. The level of risk is quantified using a measure called Customer Minutes Lost (CML). This measure corresponds to the number of minutes per year the average consumer is affected by failure. To retain transparency, CML is calculated and presented separately for quantity and quality failures. Furthermore, the probability of failure as well as the failure rate and duration of failure are calculated for all events included in the fault tree analysis.

Göteborg Vatten has worked out an action plan which, among other things, contains performance targets regarding the supply of drinking water (e.g. water quantity and quality targets). These targets are politically established and can be considered as tolerable levels of risk. The targets related to water quantity, i.e. the ability to deliver water to the consumers, are compared to the results of the fault tree analysis.

To analyse and evaluate the risks in Göteborg's drinking water system the following questions are to be answered:

- What is the level of risk (expressed as CML) related to quantity- and quality failures respectively?
- Is the level of risk acceptable (tolerable), referring to the defined performance targets?
- Which part of the system (from source to tap) contributes most to the total risk level?

In order to also evaluate the applicability of the fault tree method, the following questions should be answered:

- What aspects are important to consider when a fault tree analysis of a drinking water system, from source to tap, is conducted?
- How should a fault tree analysis be structured and what is a suitable level of detail for an analysis comprising an entire drinking water system?
- Is Customer Minutes Lost (CML) a suitable measure for expressing risk related to drinking water system?
- How should expert judgments be used to estimate probabilities and consequences of events where no or very limited hard data exist (e.g. measurements and statistics on events)?

1.3 Methodology

1.3.1 Introduction

The drinking water system in Göteborg was analysed by means of a probabilistic fault tree method. When identifying hazards and estimating the risk an integrated *from source to tap* approach was applied to include conditions in the source waters, treatment systems and distribution network. In this section (1.3.1) the main failure types included in the analysis are described and the fault tree technique is presented in Section 1.3.2. The risk measure (Customer Minutes Lost) and the handling of uncertainties are described in Sections 1.3.3 and 1.3.4 respectively. Further details on the fault tree method are provided by Lindhe *et al.* (2008a) and Norberg *et al.* (2008).

The overall failure event studied in the analysis was named *supply failure*. This failure may arise due to: (1) quantity failure, i.e. no water is delivered to the consumer; or (2) quality failure, i.e. water is delivered but does not comply with existing water quality standards. Based on the Swedish quality standards for drinking water, set by the National Food Administration (SLV, 2001), quality failure was defined as when the drinking water is *unfit for human consumption*. Figure 2 shows the two types of failure and how they may occur.

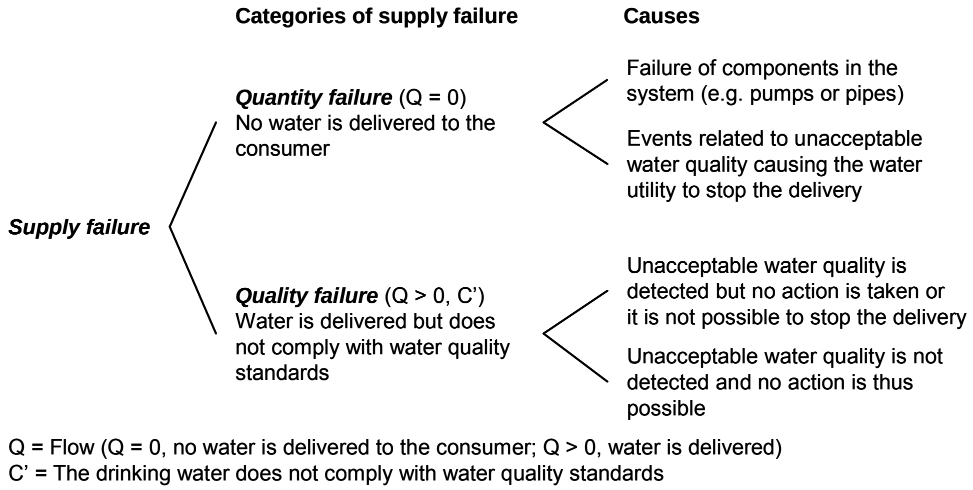

Figure 2. Categories of supply failure and their main causes (Lindhe et al., 2008a).

To analyse the entire drinking water system, it was divided into three sub-systems: raw water, treatment and distribution. The main reason for this division was to make it possible to calculate which part of the system contributes most to the total risk. Another reason was to show more easily how different parts of the system may compensate for failure in other parts. For example, if the raw water sources are unavailable due to an accident, this does not immediately cause an interruption in the delivery to the consumers. Water stored at the treatment plants and in the distribution system can be used to compensate for the failure during a limited time.

The main reasons for using a fault tree to model the Göteborg system was the complexity of the system and the interactions between events that were identified. One reason the system is considered to be complex is the use of several water sources that may supply the two treatment plants in different ways. By means of a fault tree it is possible to structure a complex system as that in Göteborg and consider interactions between events.

1.3.2 *Fault tree analysis*

Fault tree analysis is a tool used to analyse how different events may cause system failure. Starting with the *top event*, corresponding to system failure, the tree is developed until the required level of detail is reached. Events initiating failure are denoted *basic events* and logical combinations of these are denoted *intermediate events*. To model interconnections between events, logic gates are used. The two most common logic gates are the OR- and AND-gate. The OR-gate corresponds to a series system where only one input event has to occur to cause failure. The AND-gate is used to model a parallel system where all input events have to occur to cause failure. Figure 3 shows an example of a fault tree where system failure occurs if pump failure *or* pipe failure occurs. For pump failure to occur, pump no. 1 *and* pump no. 2 need to fail at the same time. In order to model a drinking water system's ability to compensate for failure, additional logic gates are needed. In addition to the OR- and AND-gate, two variants of the AND-gate were used. These logic gates are described below and the theoretical foundation of them is further described by Norberg *et al.* (2008).

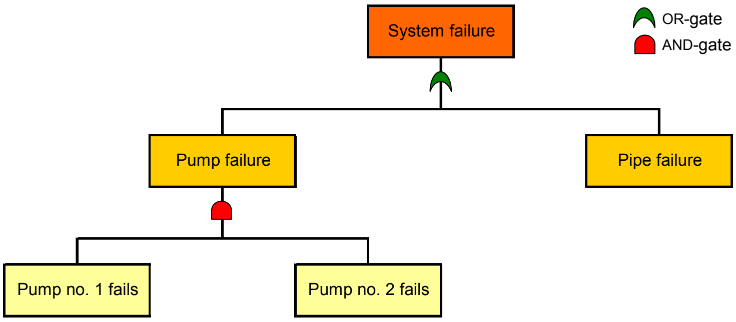

Figure 3. Fault tree illustrating the OR*- and* AND*-gate.*

The first variant of the AND-gate models the ability of one or more components to compensate for failure during a limited period. For example, a service reservoir may compensate for failure when water cannot be distributed to a specific delivery zone. However, since the reservoir volume is limited also the time that failure may be compensated for is limited. When a component cannot compensate for failure it fails and consequently also the system fails. Also the second variant of the AND-gate models compensation but includes the possibility of a compensating component that has failed to recover. For example, an unacceptable high concentration of a parameter in the raw water may to a certain extent be compensated for by the treatment. However, failures in the treatment plant may affect the treatment efficiency and consequently compensation may no longer be possible. When the treatment plant is operating normally again, the treatment efficiency is up to normal and compensation is possible. In some cases the concentration may be too high or the specific parameter cannot at all be compensated for.

The analysis was based on a Markovian approach (Rausan and Høyland, 2004). This means that an event is considered to either occur (1) or not occur (0) and the transition between these states (1 and 0) are in the fault tree described using the mean failure rate (λ) and the mean downtime ($1/\mu$). The failure rate represents the frequency with which an event occurs and this information may also be expressed as the mean time to failure ($1/\lambda$). The downtime is equal to the duration of failure and variable μ corresponds to the repair rate. Based on these variables the probability of failure can be calculated as $P_F = \lambda/(\lambda + \mu)$. Since the probability of failure can be calculated based on the failure rate and downtime this facilitates the use of expert judgments. It is considered easier for experts to estimate the failure rate (or time to failure) and downtime instead of directly estimating the probability of failure. The equations used to calculate the outcome of the different logic gates are given in Table 1. The events modelled using the OR- and AND-gate are described by the mean failure rate (λ) and the mean downtime ($1/\mu$). However, for the two variants of the AND-gate additional variables are needed to model the ability to compensate for failure.

When using the two variants of the AND-gate, the event that may be compensated for is modelled in the same way as described above for the OR- and AND-gate. However, the events corresponding to compensating components are described differently. For these events variable λ was obtained by estimating the time compensation is possible ($1/\lambda$). Only the second variant of the AND-gate includes the ability of a compensating component to recover after failure. Consequently, the mean downtime ($1/\mu$) of compensation was only estimated for compensating events modelled using the second variant of the AND-gate. To model a compensating component also the probability of failure on demand (q) has to be included. Failure on demand means that compensation is not possible at all. For example, if a reserve pump does not start when needed, it fails on demand. If the pump start but fails after a certain time it fails during operation, which is represented by the failure rate. The probability of failure on demand was estimated for the compensating events in both variants of the AND-gate. All equations used to calculate the output of the different logic gates are presented in Table 1. By calculating the output of each logic gate and using it as input in the next level of the fault tree, the results for the top event are finally determined.

Table 1. Equations used to calculate the output of the logic gates. For the variants of the AND-gate $i = 1$ corresponds to the failure event that may be compensated for by events $i = 2, \ldots, n$. For the second variant only one compensating event is considered, $i = 2$. 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 (Lindhe et al., 2008b).

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

1.3.3 *Risk as Customer Minutes Lost (CML)*

The risk (R) was expressed as the expected value of Customer Minutes Lost (CML), i.e. the number of minutes the average consumer is affected by failure. Thus, for quantity-related failures CML is equivalent to the number of minutes per year the average consumer is not supplied with drinking water. Correspondingly, for quality-related failures CML is equivalent to the number of minutes per year the average consumer is exposed to drinking water unfit for human consumption. The CML values were calculated and presented separately for quantity and quality failures. Lindhe *et al.* (2008a) provides a detailed description of the measure. Blokker *et al.* (2005) describes the use of CML as a performance indicator in the Netherlands. CML may be calculated as the product of the mean failure rate (λ), mean downtime ($1/\mu$) and the proportion of consumers affected (C). However, 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.*, 2008a). Since events at a high level in the fault tree are combinations of different types of events, the number of people affected cannot easily be defined for these events. Instead, the number of people affected was defined at a lower level for n different types of events. The total risk was thus calculated as:

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

1.3.4 *Uncertainties*

To include uncertainties in input variables, they were expressed as probability density functions and the calculations were performed using Monte Carlo simulations (10,000 iterations). Variables λ and μ were modelled as rates based on exponentially distributed times, using Gamma distributions. Beta distributions were used to model the proportion of the consumers affected (C) as well as the probability of failure on demand (q). The main reasons for using Beta and Gamma distributions to model input variables are that they facilitate a Bayesian approach and are flexible and can attain a vide variety of shapes. A Bayesian approach means that hard data and expert judgments can be combined and new information, e.g. monitoring data, can be used for a mathematically formal updating of previous knowledge (Bedford and Cook, 2001). Furthermore, Monte Carlo simulations facilitate two important types of analyses: (1) sensitivity analysis of contributions to the total uncertainty from uncertainties in basic events; and (2) analysis of the probability that the water supply does not meet established performance targets.

1.4 Limitations

Quality failure was defined to occur when the drinking water is *unfit for human consumption*, according to national quality standards on drinking water. The identification and analysis of events that may cause quality failure were based on health-related parameters as specified in the present Swedish drinking water regulations (SLV, 2001), except for the raw water where microbial quality was tested against the former Swedish drinking water regulation (SLV, 1993). This means, for example, that parameters only affecting the aesthetic quality of the drinking water were not considered. However, in future analyses it is possible to include also other quality parameters.

The fault tree analysis is used to calculate, among other things, CML due to quality failure. The quality-related CML is an estimation of the expected number of minutes the average consumer is exposed to drinking water unfit for human consumption. The health effect of consuming drinking water unfit for human consumption is, however, not considered. In order to do so, a more detailed chemical and/or microbiological analysis including dose-response assessments needs to be performed. The results from the fault tree analysis could be used as input to, for example, a Quantitative Microbial Risk Assessment (QMRA).

2 System description

2.1 Overview

2.1.1 *General facts about the Swedish drinking water supply*

Sweden has 290 municipalities and the median size of a municipality is only 16,000 inhabitants where the largest, Stockholm, has more than 700,000 inhabitants and the smallest less than 3,000. Sweden has slightly over 2,000 publicly owned water works that serve about 7.7 million people (90% of the total population). Approximately half of the raw water originates from surface water and the other half from groundwater sources, see Table 2.

Table 2. Characteristics of Swedish drinking water supply.

	Surface water	Groundwater	
		Natural	Artificial (infiltrated)
Number of works	200	1700	140
Share of total production (vol %)	51	26	23

Total annual drinking water production amounts one billion cubic meters, equivalent to 310 l/p d. Total length of the water distribution network is about 71,000 km and the pipe materials are mainly cast iron, plastic and steel.

2.1.2 *The Göteborg system*

Göteborg is the second largest city in Sweden and the local water utility, Göteborg Vatten, supplies approximately 500,000 people with drinking water. Primarily, the raw water (Section 2.2) is taken from River Göta älv. In addition to the river a number of interconnected lakes are supplying Göteborg with raw water during periods when the water quality of River Göta älv is considered unsafe for drinking water production. Two drinking water treatment plants, Alelyckan and Lackarebäck (Section 2.3), are treating all drinking water for Göteborg. In 2007 a total volume of 60.5 Mm^3 was produced. The distribution network (Section 2.4) comprises of about 1,700 km of pipes. System figures and additional key numbers for the water production for the year 2007 are listed in Appendix A.

2.2 Source water

The city of Göteborg is located at the Swedish west coast and has its primary raw water intake from the river Göta älv, see Figure 4. The entire catchment area, including areas of the upstream Lake Vänern and further upstream rivers, is the largest in Sweden (50,200 km^2). In the north-west the catchment area is bridging the border to Norway. The lower part of the catchment, from Lake Vänern to the sea (Figure 4), comprises an area of 13,300 km^2 and Göta älv has an annual mean flow of 550 m^3/s.

High flows in Göta älv (>500 m^3/s) are normally registered from December to June, while low flows (<500 m^3/s) mainly occur between July and November. Hydropower stations regulate the flow from Lake Vänern to the sea and seasonal flow variations registered in Lilla Edet (Figure 4) are in the range of 200-900, with extreme flows up to 1,200 m^3/s. Hydropower stations are installed in Vänersborg, Trollhättan and Lilla Edet, as indicated in Figure 4. These hydropower stations are the main cause for flow variations in Göta älv.

In the downstream part at Kungälv, the river splits and flow around the island of Hisingen (Figure 4). The northern branch has the largest water flow of about 75% and the southern branch (still referred to as Göta älv) the remaining 25%. A flow shield is located in the northern branch and regulates the flow in both branches. The flow shield can be used to ensure sufficient flow in the southern branch in order to prevent saltwater intrusion from the sea. The residence time from Lake Vänern to the sea through Göta älv varies from 1.5 to 5 days, with a mean of about 3 days (GÄVVF, 2006).

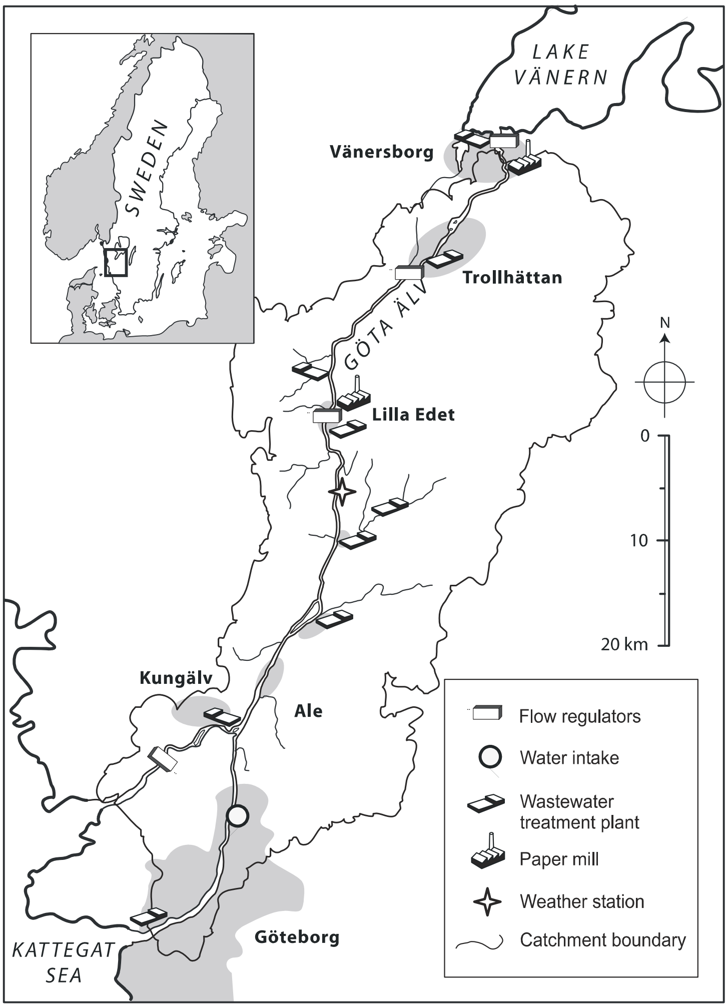

Figure 4. River Göta älv and its lower catchment with the location of wastewater treatment plants, paper mills and the raw water intake for Göteborg.

Point source pollution to Göta älv upstream the raw water intake in Göteborg includes human pollution due to discharge from nine municipal wastewater treatment plants (serving approximately 110,000 persons) and discharge from 13 larger industries, including paper mills. The microbial impacts from diffuse sources mainly result from surface runoffs, from urban and rural areas and contamination from birds and animals.

Seven monitoring stations are located along Göta älv between Lake Vänern and the raw water intake in Göteborg, acting as an early warning system for the drinking water treatment plants. Parameters continuously monitored on-line are water temperature, turbidity, conductivity, redox-potential and pH. Microbial sampling of indicator organisms is regularly carried out at three of the stations upstream the raw water intake. At the raw water intake an automated microbial sampling system, *Colifast* (Braathen *et al.*, 2005), measures the total coliforms two times per day. During the last two years, the Colifast equipment has been used to enhance the microbial monitoring within the area located upstream the water intake for Göteborg.

From the intake at River Göta älv, raw water is transferred to Alelyckan and Lackarebäck treatment plants. The raw water intake is regularly closed, approximately 100 days per year, due to various hazardous events identified either by on-line monitoring or by reports from operating bodies upstream (e.g. municipalities and industries). In general, closure of the raw water intake can be due to:

1. precipitation, resulting in e.g. sewer overflows with microbial discharges;
2. accidental discharge, e.g. discharge of manure, wastewater or chemicals;
3. activities in or near the river, e.g. dredging or building activities; or
4. saltwater intrusion, i.e. water from the sea reaches the raw water intake.

When the intake from River Göta älv is open, the raw water enters into a basin next to the river. From this basin, water flows by gravity through a tunnel both to the Alelyckan treatment plant and to a pumping station 90 metres below ground near the lake Härlanda tjärn, see Figure 5. The water is then pumped from the station up to another tunnel and further into lake Lilla Delsjön, that is connected to the lake Stora Delsjön (together constituting Lake Delsjön). From Lake Delsjön the raw water flows through a tunnel into the Lackarebäck treatment plant. During periods when the river intake is closed, Alelyckan is also supplied from Lake Delsjön by reversing the flow in the tunnels. Lake Delsjön provides a raw water volume sufficient for a continuous water supply of up to three weeks when the raw water intake in Göta älv is closed. In addition to Lake Delsjön, water from a reservoir lake (Lake Rådasjön) in a backup raw water supply system can be used to prolong the possible supply of raw water with approximately one month.

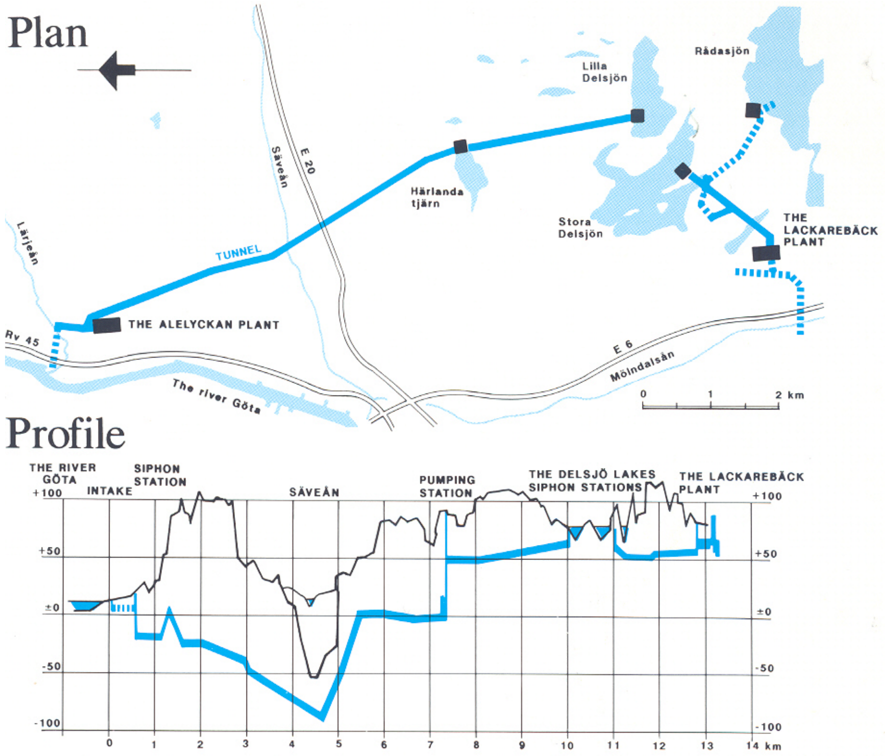

Figure 5. The raw water supply in Göteborg including a profile of the tunnel transport system between River Göta älv and Lake Delsjön.

2.3 Treatment

The drinking water treatment plants at Alelyckan and Lackarebäck includes 6 and 7 treatment lines respectively. The maximum production capacity of the two plants is 150,000 and 120,000 m^3/d respectively (average total production is 168,000 m^3/d). Due to maintenance work the production capacities are normally lower than maximum. The drinking water demand varies between 120,000-210,000 m^3/d. The retention time within each plant is about 8-10 h. After raw water is pumped to the plants it flows through the plants by gravity. The treatment steps for producing safe drinking water include chemical flocculation, sedimentation, filtration and disinfection (see Figure 6 and Figure 7). On-line measurements of pH, chlorine and turbidity are located at several locations along the treatment lines. In addition, laboratory analyses are regular carried out.

Raw water adjustment

Lime is added to adjust the pH of the raw water entering the treatment plants. During periods with raw water temperatures of 12°C or above, chlorine is used for pre-disinfection at Lackarebäck.

Chemical flocculation

The raw water flows through screens at the intake to remove large objects like stones, fish, leaves etc. The removal of finer particles, such as dissolved colloids and natural organic matter (NOM), starts by adding aluminium sulphate as a flocculation agent to the flocculation tank. The dissolved substances coagulated to larger flocs.

Sedimentation

Particles aggregated to flocs are removed from the water phase mainly through sedimentation in the settling tanks. The retention time is about 4 h. In the Lackarebäck plant one of the basins has been rebuilt and now consists of a lower sedimentation tank and an upper flotation basin.

Granular activated carbon filtration (GAC)

The remaining suspended particles and unsettled flocs are finally removed in a granulated activated carbon filtration step with a retention time of about 20 minutes. The GAC filter also adsorbs substances causing taste and odour problems. The filters are backwashed every 1-2 day and the carbon is reactivated with an interval of four years.

pH-adjustment and disinfection

The pH is adjusted by adding sodium hydroxide, lime and carbon dioxide to the water. To reduce corrosion of metal distribution pipes the pH is adjusted to 8. At both treatment plants chlorine and chlorine dioxide are used as disinfection agents. Disinfection by means of ozone can be undertaken at one of the treatment lines at Alelyckan, see Figure 7.

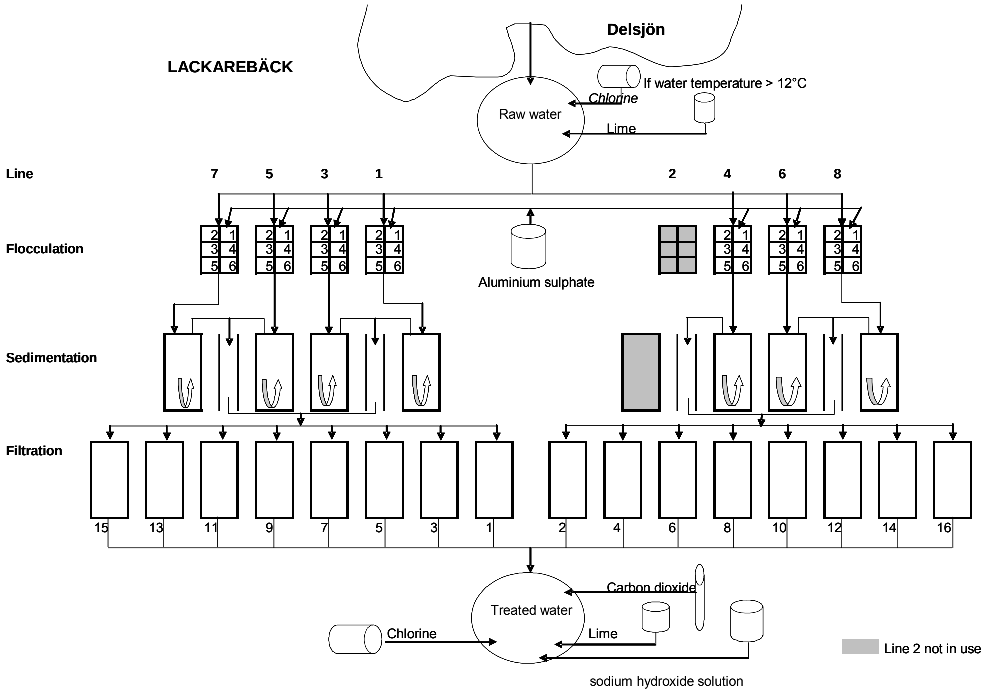

Figure 6. Lackarebäck treatment plant.

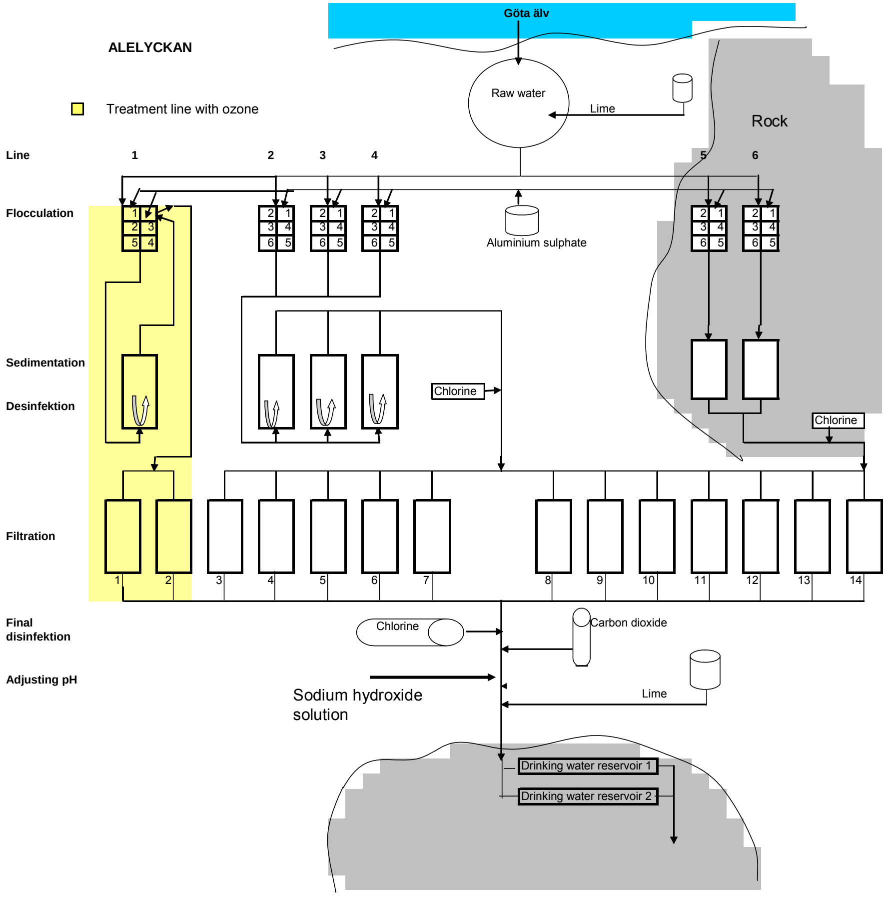

Figure 7. Alelyckan treatment plant.

2.4 Distribution

In Göteborg the distribution network is supplied with water from two treatment plants. The northern part of the network is supplied with water from Alelyckan treatment plant and the southern part is supplied by Lackarebäck treatment plant, see Figure 8. A mixed zone supplied by both plants also exists. The extension of the mixed zone depends on present consumption and the amount of water pumped into the system from each plant.

The distribution network is approximately 1,700 km in length and pipe material consists mainly of iron (67%) and plastic (24%, mainly polyethylene). To ensure sufficient pressure in areas at high altitudes (59 different pressure zones) 66 booster stations are operated. For low altitude areas pressure reduction is undertaken. In order to balance variations in consumption and supply from the two plants on a daily basis, 13 reservoirs with a total volume of 72,000 m^3 are situated in different pressure zones. At the treatment plants 4 drinking water storage tanks are also in use, with a total volume of 52,000 m^3. The pressure at the consumers tap has to be in the range of 150 to 700 kPa. Maximum pressure in the water main is 900 kPa.

Pipe corrosion and external loads are common reasons to pipe bursts that cause water leakage. In 2005 the total amount of water losses in the distributions system was 10.6 Mm^3 (18%). During the same year 382 pipe breaks were repaired. Some numbers and ratios of leakage, pipe breaks and consumer complaints in the Göteborg distribution network are:

- Number of pipe breaks per 10 km and per year: 2.3
- Number of complaints per 1,000 consumers and per year: 0.3
- Disruption time, minutes per consumer and per year (equivalent to Customer Minutes Lost): 6 minutes

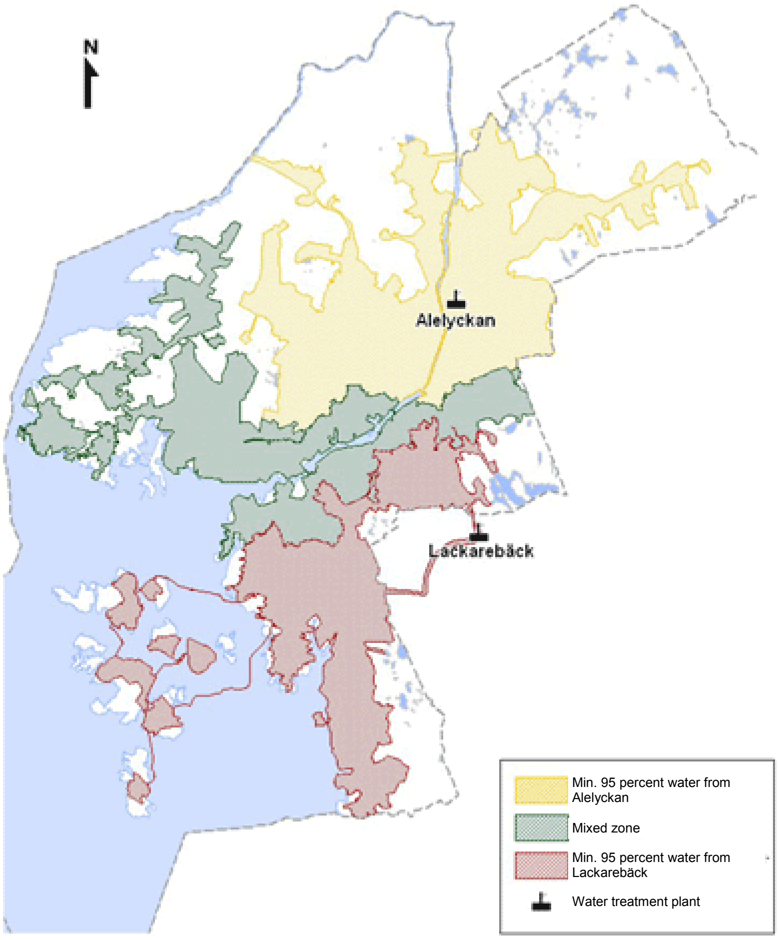

Figure 8. Drinking water supply zones in Götenborg during normal operation on an average day (distribution input 165 000 m^3/d) (Göteborg Vatten, 2008).

2.5 Earlier incidents and problems

Incidents that may cause risks to the consumers occur in the source waters, in the treatment plants, in the distribution system or as a combination of events. Historically, incidents in River Göta älv resulting in closure of the raw water intake have been related to various contaminants. Compared to the raw water system, incidents in the water treatment are rare. In the distribution network the most common problems are related to pipe bursts caused by corrosion.

2.5.1 *Incidents related to the quality and supply of source water*

Most incidents in the Göta älv catchment area have mainly been of chemical or physical nature. However, incidents of microbial nature are considered as most harmful for the consumers. In addition to the on-line monitoring system, several incidents have been identified by reports regarding contaminants from operating bodies upstream. Regular closures of the river water intake are used to prevent contaminants to enter the Alelyckan treatment plant. This flexible intake can be regarded as an initial barrier of the supply system. The efficiency of the intake closures as a barrier has been shown most efficient for faecal indicator bacteria compared to pathogenic organisms (Åström *et al.*, 2007a; Åström *et al.*, 2007b).

Untreated wastewater is frequently discharged to River Göta älv from urban areas and this is the dominating type of microbial incident reported along the river. Overflows from combined and separate sewers occur mainly during heavy rainfalls and take place in almost all of the upstream municipalities (Åström *et al.*, 2008). Emergency discharges of wastewater do also occur, e.g. in 2004 when a sewer pipe break was reported. In addition to wastewater discharges, the microbial events include manure discharge accidents (one single occasion, 2001) and rural runoff including a potential spread of zoonotic pathogens from runoff of farmlands with grazing animals. Turbidity monitoring is used to provide a rough measure of microbial discharges associated with transport of suspended particles during urban and rural runoffs along the river.

Non-microbial incidents/events also occur in Göta älv, such as chemical discharge from upstream industries. Recent years this included spills of sodium hydroxide from an upstream chemical industry as well as oil spills from ships. Saltwater intrusion from the sea also leads to closure of the raw water intake in Göta älv. Elevated conductivity is used to register intrusion of saltwater.

Rock tunnels are in use to transport raw water from River Göta älv to Lake Delsjön and further on to Lackarebäck water treatment plant. During periods when water from River Göta älv is considered unsafe for drinking water production, the river intake is closed and Alelyckan treatment plant is supplied with raw water from Lake Delsjön, by reversed flow direction in the tunnel. A collapse of the rock tunnels would have severe effects on the supply of raw water. The risk related to the rock tunnels have previously been studied in a risk analysis, see Rosén and Steier (2006).

2.5.2 *Incidents related to the treatment*

Incidents in the treatment plants have occurred and in some cases the water utility has decided to not deliver parts of the treated water to the consumers. One or several treatment lines can be *switched off* if problems occur and are identified by means of, for example, on-line measurements and laboratory analyses. To ensure the reliability of the treatment plants they are split up in several lines and backup components are included. If failure affecting the water quality occurs, it is possible to quickly drain parts of the plants. For example, the drinking water storage tanks at the Lackarebäck plant may be quickly drained. In case of a power failure, backup power supply systems can supply electricity for 85-90% of the normal treatment capacity.

Chemicals for coagulation and disinfection are kept in stocks at the treatment plants. At the Alelyckan treatment plant the stock of coagulation chemicals is much smaller and the storage tower is therefore now being rebuilt to increase the storage capacity. For lime and sodium hydroxide there are stocks that last for about two to three weeks. In case of a shortage of lime only sodium hydroxide solution is used.

2.5.3 *Incidents related to the distribution*

Pipe bursts in the distribution network is mainly a result of corrosion and external stress. Corrosion can occur both internal and external. The internal corrosion is effected mainly by unfavourable water quality and the external corrosion by local soil composition (marine clay in Göteborg). For internal as well as external corrosion the pipe material is of great importance. External stresses on the pipes that may cause pipe breaks are, for example, soil settlements and traffic loads. Active leakage control is practiced by leak detection of mains and monitoring flow and pressure.

To prevent disruption of water supply to the consumers the following actions may, for example, be undertaken in the distribution network:

- Temporary supply by tubing connected to fire hydrant
- Delivery of water by means of bowsers
- Backup power supply to pump stations

3 Risk analysis

The risk analysis includes: scope definition (Section 1); system description (Section 2); hazard identification (Section 3.1); risk estimation by fault tree construction, evaluation of available data and expert judgements (Section 3.2); and sensitivity analysis (Section 3.3). The different steps were carried out and continuously updated based on feedback from the ongoing work. A team of people (water utility personnel and researchers) with different knowledge about the system and the risk analysis method was set up to support the analysis work.

3.1 Hazard identification

To structure the fault tree a system description was required as well as an identification of hazardous events. The fault tree construction and identification of hazards were done simultaneously. The hazard identification was conducted based on brainstorming, experience from the past and utilizing the TECHNEAU Hazard Database (THDB) (Beuken *et al.*, 2007).

The two types of failure included in the analysis were quantity and quality failure (Section 1.3.1). Quantity failure may be caused either by failure of components in the drinking water system, making it impossible to supply the consumer with water, or due to unacceptable water quality (raw water or drinking water) causing the water utility to stop the delivery. Quality failure may occur when an unacceptable water quality is not detected or it is detected but no action is possible (Figure 2).

Events causing failure as well as the systems inherent ability to compensate for failure were identified. Totally 116 basic events (failure events and compensation events) were identified. How these events were used to construct the fault tree is further described in Section 3.2.

3.2 Risk estimation

3.2.1 Fault tree

General structure of the fault tree

As described in Section 1.3.1 the drinking water system was divided into its three main sub-systems (raw water, treatment and distribution), see Table 3. Figure 9 shows a schematic fault tree including the main types of events that may cause supply failure (i.e. quality or quantity failure). In the figure, examples of the OR-gate and the first variant of the AND-gate are shown. An OR-gate shows that only one sub-system has to fail to cause supply failure. Furthermore, OR-gates are used to illustrate that failure in each sub-system can occur due to quantity or quality failure. In case failure occurs in a sub-system that may be compensated for during a limited period. This is modelled using the first variant of the AND-gate (Figure 9). Consequently, supply failure only occurs if the specific sub-system fails and no compensation is available. Note that although quantity and quality failures are included in the same fault tree, the results are presented separately to retain transparency.

Table 3. Description of the raw water, treatment and distribution system.

Part of system	Description
Raw water	The raw water system includes the catchment area, the raw water intake, the entire supply system (i.e. pumps, siphons, tunnels etc.) and everything to the point where the raw water enters the treatment plants.
Treatment	From the point where the raw water enters the treatment plants, throughout the plants to the point just before the treated water is pumped out to the distribution network, is included in the treatment part.
Distribution	The distribution system includes all components (pumps, pipes, service reservoirs etc.) starting at the point where the treated water is pumped out from the plants all the way to the tap.

When failure in one part of the system was identified, it was based on the assumption that the previous parts of the system were operating normally (i.e. no failure related to previous parts). One of the reasons for separating the different sub-system was to simplify the hazard identification, i.e. focus one part of the system. For example, when events were identified that cause quality failure within the treatment system, it was assumed that no failure occurs in the raw water, i.e. the used raw water fulfilled the quality standards. Another reason for separating the three sub-systems was to make it possible to compare how much the different sub-systems contribute to the total risk level. Although hazards were identified for each sub-system separately, the fault tree model considers that failures may occur simultaneously in different sub-systems.

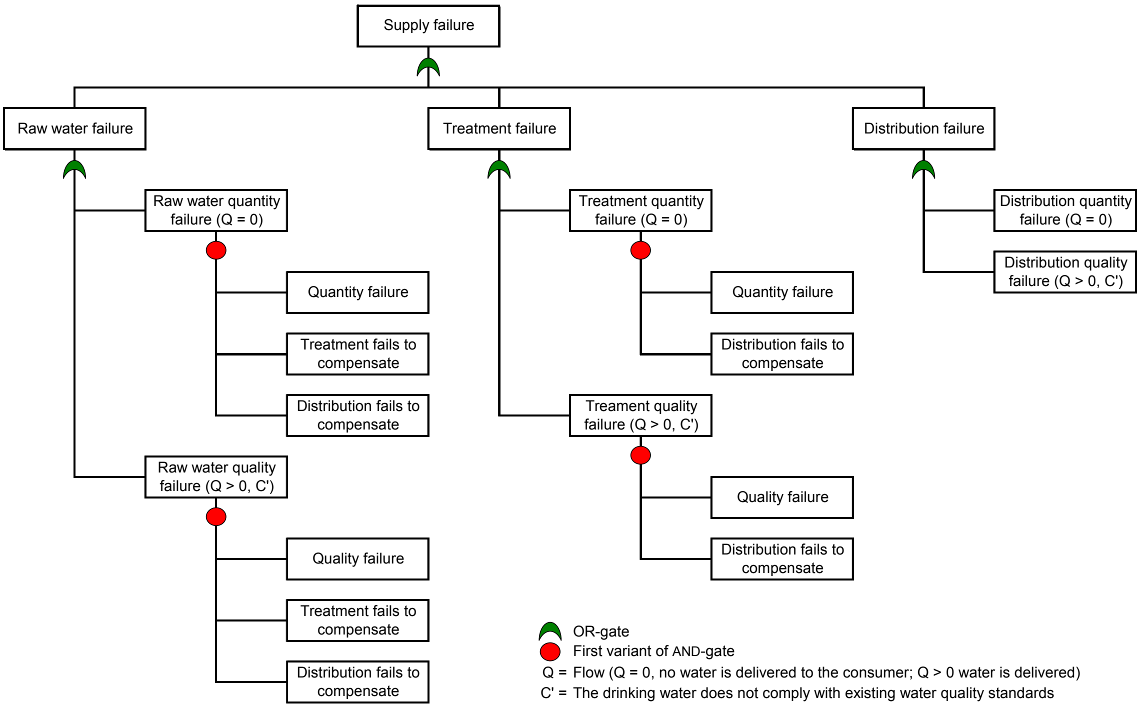

Figure 9. Schematic fault tree illustrating the main type of events (Lindhe et al., 2008b).

Figure 9 is a schematic fault tree illustration how drinking water systems can be modelled. To model the Göteborg system this fault tree was developed in detail by including all events that may cause supply failure. The detailed fault tree also included the traditional AND-gate and the second variant of it (Section 1.3.2). Totally the fault tree of the Göteborg system was composed of 116 basic events, 100 intermediate events and 101 logic gates.

Raw water system in the fault tree
The system description of the raw water system (Section 2.2) shows that the supply of raw water in Göteborg is complex. Several events may cause quantity and quality failures, but there are also possibilities to compensate for these failures. The fault tree was structured to model that supply failure may occur due to problems in the supply of raw water to any of the two treatment plants. For quantity failure to occur, all raw water sources have to be unavailable for at least one of the treatment plants. However, this failure may be prevented by the drinking water storage tanks in the treatment plants, by increased production capacity at the non-affected treatment plant and by the reservoirs in the distribution system. Since these compensations are time limited, the first variant of AND-gate was used to combine these events. To describe the ability to compensate the probability of failure on demand (q) and mean failure rate (λ) were used. The failure rate was based on the time period compensation is possible ($1/\lambda$).

Events that may cause the water sources to become unavailable (quantity failure) are related to failure of physical components (e.g. rock tunnels, pipes, pumps, siphons) or the actual quality of the raw water. Events affecting the raw water quality and guiding the water utility to close the raw water intake in the river are mainly related to precipitation, saltwater intrusion from the sea and accidental releases of contaminants (Åström *et al.*, 2007a).

Quality failure may occur when raw water of unacceptable quality is supplied to the treatment plants. This may happen when a quality deviation is not detected or when no actions are possible, although the quality deviation is detected. Measurable as well as non-measurable parameters where included to model quality failures related to the raw water. Even if raw water of unacceptable quality is used to produce drinking water, the drinking water can still fulfil the quality standards, by suitable treatment. Hence, the ability of the treatment to compensate for unacceptable raw water quality was included in the fault tree with the second variant of AND-gate. The probability that the unacceptable water quality can be compensated for at all was represented by the probability of failure on demand (q). The mean failure rate (λ) and mean downtime ($1/\mu$) describe how often the treatment efficiency is affected and for how long.

Faecal indicator bacteria have been found to regularly exceed the national quality standards for drinking water (SLV, 2001) far more often than other quality parameters (Göteborg Vatten, 2006). Hence, the main focus was on microbiological hazards when quality failure events in the raw water system were identified.

Treatment system in the fault tree
Supply failure may occur due to failure in any of the two treatment plants. Quantity failure may occur due to physical damage of the treatment plant and due to failure of treatment processes that result in unacceptable water quality. An unacceptable water quality may only cause quantity failure if the water utility detects the failure and decides to stop the delivery. If the failure is not detected, or the water utility decides not to stop the delivery because that would cause greater risks, quality failure instead occurs. Drinking water storage tanks in the treatment plants as well as reservoirs in the distribution system may compensate for quantity failures in the treatment plants for a limited time. They are therefore modelled by the first variant of the AND-gate.

Microbiological hazards were considered as the most important in the raw water system. Hence, the focus when identifying quality failures in the treatment was on events that may reduce the removal of microbiological agents.

Distribution system in the fault tree
Quantity failure in the distribution system may occur due to: (1) water cannot be transferred from the treatment plants to the distribution system; (2) breaks in water mains, distribution pipes or service connections; (3) failure of pumps in specific delivery zones; or (4) failure in private buildings. Depending on the event, quantity failure in the distribution system may be compensated for by reservoirs in the distribution system during a limited time. Problems related to water mains cause quantity failure when two pipe bursts occur at the same time, or when one pipe burst occurs simultaneously as the supply of water from the treatment plants is limited (making it hard to retain prescribed pressure in the system).

Quality failure related to the distribution system may occur due to microbial growth, intrusion of contaminants and quality failure in private buildings. Since the number of people affected varies, these events were divided into major and minor events. In this part of the fault tree no compensation was considered, since there are no barriers that may compensate for quality failures in the distribution.

3.2.2 Input data

When available, hard data (e.g. measurements and statistics on events) were used to estimate probability distributions for the required input variables (see Section 1.3.2). When the hard data were not sufficient, expert judgements were used. In some cases only expert judgements were used and in some cases a combination of expert judgements and hard data was used. The experts (mainly water utility personnel) were asked to estimate a probable highest and lowest value of the variable and this information was used as percentiles when defining the probability distributions. Also mean values were estimated by the experts and considered when defining the probability distributions.

3.2.3 *Results and discussion*

The results of the fault tree analysis are summarised in Figure 10 and Figure 11. The figures show risk levels (CML), probabilities of failure, failure rates and downtimes for the entire system and the three sub-systems. Uncertainties of the results are also included in the figures. The results for quantity (Figure 10) and quality failure (Figure 11) are presented separately. The calculations were performed by means of Monte Carlo simulations (10,000 iterations).

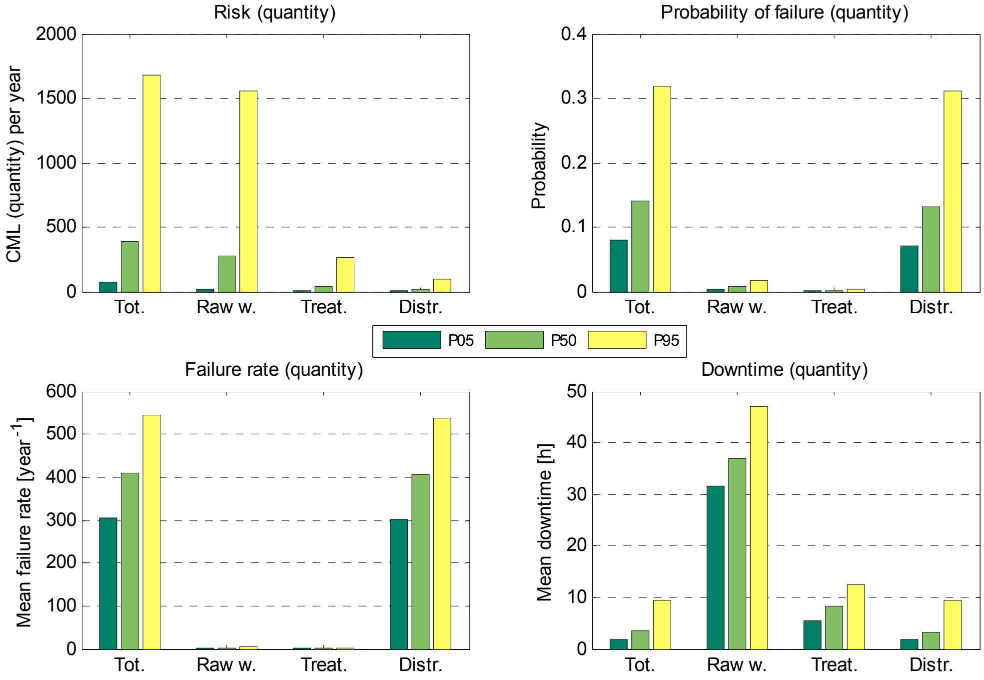

Figure 10. Histograms showing the results of quantity failure. Risk (expected value of CML), probability of failure, mean failure rate and mean downtime are presented for the entire system (Tot.) as well as the three sub-systems (Lindhe, 2008).

Figure 10 shows that the total risk level (CML) for quantity failure is mainly due to failures related to the raw water system. The probability of failure is highest for the distribution system. Although the probability is high, the downtime is short and a small number of consumers are affected. Consequently the distributions failures have a small influence on the total risk level (Figure 10). In contrast to the distribution system the raw water system seldom fails (low failure rate) but has a long mean downtime and affect many consumers. Failures in the treatment may affect many consumers but the low failure rate and short downtime result in a small contribution to the total risk level.

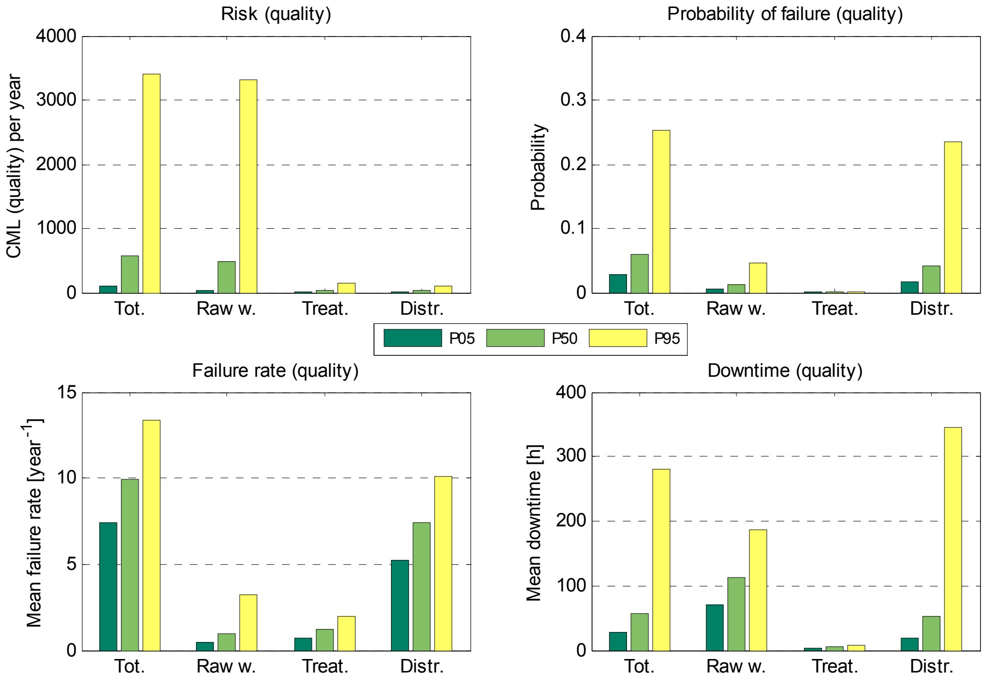

Figure 11. Histograms showing the results of quality failure. Risk (expected value of CML), probability of failure, mean failure rate and mean downtime are presented for the entire system (Tot.) as well as the three sub-systems (Lindhe, 2008).

The results for quality failure in Figure 11 can be explained in a similar way as the results for quantity failure in Figure 10. The raw water system contributes most to the total risk level and the distribution system causes frequent failures that have short durations and affect few consumers. From the rates of failure (Figure 10 and Figure 11), it appears that the quality failures occur more seldom than quantity failures. The risk levels (CML) on the other hand show that the total risk level is higher for quality failure. This is mainly due to the duration (i.e. downtime) of failure in the raw water and distribution system is longer for quality failure compared to quantity failure. However, the consequences of quantity and quality failures are not the same and the risk levels should not be directly compared.

Both figures (Figure 10 and Figure 11) show that the uncertainties of some results are high. Information like this is important and should be considered when evaluating the results. This is further discussed in Section 3.3.

It should be noted that the results presented here are based on the assumptions made when constructing the fault tree and estimating the variables. These assumptions need to be further analysed by involved experts before the results are used as a decision support.

3.3 Sensitivity analysis

Risks always include uncertainties and consequently also risk analyses include uncertainties. Examples of uncertainties are model uncertainties and parameter uncertainties. Also linguistic uncertainties, i.e. language-based uncertainties, may occur due to e.g. unclear statements (Burgman, 2005).

In the fault tree analysis uncertainties were included by modelling all input variables as probability distributions. Calculations were performed using Monte Carlo simulations in order to also consider uncertainties in the results. To analyse how much each input variable affects the uncertainties in the results, rank correlation coefficients can be calculated. The correlation coefficient can have values between -1 and 1, where negative values represent negative correlation and positive values positive correlation. A large correlation value indicates a strong relationship between the variable and the results. The fault tree method enables calculations of rank correlation coefficients for all variables in the fault tree model. As an example, Figure 12 shows the correlation coefficients for the six variables contributing most (i.e. highest values) to the uncertainties in the probability of distribution failure. The probability of distribution failure is used as an example to illustrate how uncertainties in model results can were analysed in the Göteborg case study. By identifying variables with high correlation coefficients, it can be concluded which variables should be further studied in order to reduce uncertainties in the results. When the uncertainties in a variable with high correlation coefficient are reduced, also the uncertainties in the results will be reduced. Thus, to reduce the uncertainties in the probability of distribution failure it is most efficient to start looking at the variables in Figure 12 and see if the uncertainties may be reduced by further studies.

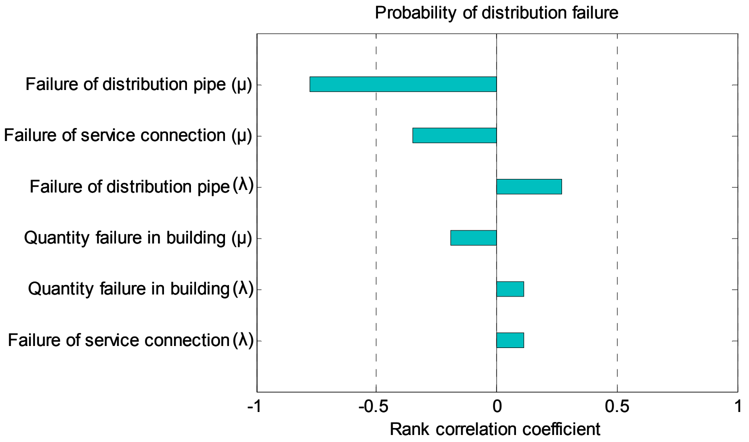

Figure 12. Rank correlation coefficients of the six variables contributing most to the uncertainties in the probability of distribution failure (Lindhe, 2008).

4 Risk evaluation

Based on the results of the risk analysis the risk evaluation aim to determine if the level of risk is acceptable or not. If the risk is unacceptable, possible options for risk reduction should be identified and analysed in order to select the most suitable one. In Section 4.1 results of the fault tree analysis is compared with existing performance targets and Section 4.2 provides a brief discussion on risk reduction options.

4.1 Risk tolerability

Göteborg Vatten has worked out an action plan which, among other things, contains performance targets regarding the supply of drinking water. These performance targets are politically established and can be considered as tolerable levels of risk. The action plan includes targets regarding the reliability of the supply and safety from a human health point of view (Göteborg Vatten, 2006). Two of the performance targets have been compared with the results of the fault tree analysis. These targets are related to the reliability of the supply:

1. 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.
2. Duration of interruption in delivery to the average consumer shall totally be less than six minutes per year, provided delivery from both water treatment plants.

The first target can be translated to an acceptable risk level of 144 annual CML for the average consumer. The second target corresponds to 6 annual CML for the average consumer. When compared to the results of the fault tree analysis, the probability of exceeding these acceptable risk levels was calculated to 0.84 and 0.58 respectively (Figure 13). The probabilities are not negligible, especially not the probability of exceeding target no. 1.

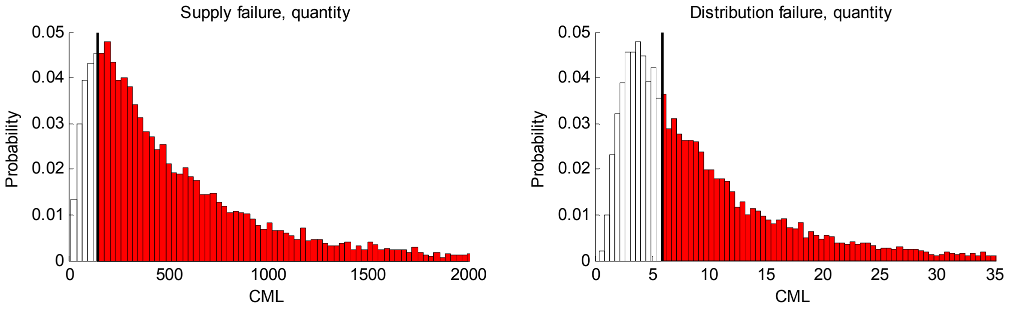

Figure 13. Uncertainty distributions of risk levels (expected value of CML) compared with performance target no. 1 (left) and 2 (right). The performance targets (144 and 6 CML per year) are indicated by solid vertical lines. The probabilities of exceeding the targets are 0.84 for target no.1 and 0.58 for target no. 2.

4.2 Risk reduction options

The results presented in Section 4.1 show that the probability of exceeding the performance targets is high: 0.84 and 0.58. Hence, options to reduce the risk have been identified and analysed. One of the options is to increase the production capacity of the treatment plants. It has already been decided that the treatment plants will be rebuilt to increase the production capacity. To model the increased production capacity, the input variables to the fault tree model were changed. The updated model showed that the probability of exceeding performance target no. 1 will decrease to 0.29 when the plants have been rebuilt (Rosen *et al.*, 2008). Also additional risk reduction options have been analysed and are described by Rosen *et al.* (2008), but is not further presented here.

5 Discussion and conclusions

This section provides a discussion and evaluation of the applied method. The results of the fault tree analysis are presented and discussed in Section 3.2.3.

5.1 Method evaluation

The method for integrated and probabilistic fault tree analysis has the ability to model an entire drinking water system, including interactions between events. Hence, a fault tree can be constructed to properly describe the analysed system. Furthermore, both quantity- and quality-related failures can be included in the analysis. The method does not include health effects of drinking water not fulfilling the quality standards but it provides an estimate of the expected number of minutes the average consumer is exposed to unacceptable drinking water quality (in this case study defined as unfit for human consumption). To also include health effects (assessing the risk of human infection) the fault tree method may be combined with, for example, a Quantitative Microbial Risk Assessment (QMRA). The fault tree provides a detailed system description that can be used to identify options to reduce the risk.

Table 4 summarises some general criteria on which the applied fault tree method is evaluated.

Table 4. Summary of the method evaluation by means of general criteria.

Criteria	Low	Medium	High
Resources needed			
Required level of expertise needed			x[1]
Time required for analysis			x[1]
Required level of data details needed		x	
Method properties			
Ability to consider a source-to-tap approach			x
Ability to include water quantity aspects			x
Ability to consider water quality aspects		x	
Ability to consider interactions between events, i.e. chains of events			x
Ability to acknowledge system structure/design			x
Ability to consider uncertainties of e.g. probabilities			x
Ability to consider/model risk reduction options			x
Ability to be integrated in the water company management/maintenance routines		x	
Updating possibilities, i.e. update when new information becomes available			x
Results			
Ability to provide understandable results to the specific end-user			x
Ability to provide input data to be used in further studies, e.g. more detailed risk analysis			x

[1] A high level of expertise and time is mainly required for constructing the fault tree. When a fault tree model is available, resources needed for collecting input data and running simulations are on a medium level.

The fault tree method provides information on risk levels (CML) as well as the dynamic behaviour of the system. The probability of failure, failure rate and downtime are calculated for all events in the fault tree, and consequently different parts of the system can be compared and knowledge gained about how the system function (i.e. the dynamic behaviour). Since risk levels are calculated for the entire system as well as the main sub-systems, it is possible to analyse which part of the system that has the highest contribution to the total risk level. Moreover, the probabilistic approach enables calculations of the probability of exceeding performance targets and acceptable levels of risk. The fault tree method also enables modelling of options for risk reduction. By changing input data, adding or deleting events the model can be changes in order to evaluate how possible options affect the risk level.

The identification of hazards and construction of the fault tree is time consuming. A team of people is required consisting of experts on the system, as well as people with knowledge about the risk analysis method. However, when the fault tree model has been constructed, the collection of data and calculations are fairly simple. The fault tree method requires data on a large number of variables. However, since expert judgments can be used when hard data is missing or not sufficient, the collection of data does not require extensive resources. In the Göteborg case study the experts (mainly water utility personnel) were asked to estimate a probable highest and lowest value of each variable. This was shown to be a suitable way of working that the experts considered practical.

CML is shown to be a valuable measure to express risk, since performance targets can be defined using the same measure. It is recommended to evaluate not only the risk levels but also the variables describing the system's dynamic behaviour. Two sub-systems may case the same risk (expressed as CML) but have different probabilities of failure (i.e. failure rates and downtimes) and affect different number of people.

Since a Bayesian approach with Gamma and Beta distributions are applied, input data can be mathematically formal updated when new hard data become available. By means of uncertainty analysis, it is also possible to identify in which part of the fault tree new information is most valuable in order to reduce the uncertainties in the results.

To model a drinking water system using a fault tree it is suitable to divide it into the three main sub-systems: raw water, treatment and distribution. Furthermore, it is important to identify interconnections between events, such as abilities to compensate for failure. A clear definition of the failure events is also important in order to facilitate communication within the risk assessment team.

5.2 Lessons learned

Based on the performed risk assessment the following important lessons have been learnt:

- A good risk assessment requires a team of people with different knowledge/expertise about the drinking water system and the analysis method.
- In order to properly model a drinking water system, its inherent ability to compensate for failure has to be considered.
- By estimating the mean failure rate and mean downtime the probability of failure can be calculated. This way of working facilitates expert judgements since the probability of failure does not have to be estimated directly.
- It is not only the results of a risk analysis that provides valuable information. Carrying out a risk analysis leads to discussions on risk issues and system function that also is an important output.

5.3 Conclusion

The probabilistic fault tree method provides a valuable tool for water utilities to perform integrated risk analysis. It has been shown that the method can be used to:

- perform integrated analyses, i.e. model entire drinking water systems;
- estimate risk levels in terms of quantity- and quality-related CML;
- understand the dynamic behaviour of the system (probabilities of failure, failure rates and downtimes);
- estimate the probability of exceeding acceptable levels of risk, or other specific criteria;
- identify the events that contribute most to the uncertainty in the results, and consequently assess where further information is most valuable to reduce the uncertainties in the results;
- update the analysis when new information becomes available;
- model risk reduction options and evaluate their efficiency; and
- facilitate discussions on risks to the system and how the system functions.

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Appendix A – System figures for the water production

System figures and other key numbers for the water production in Göteborg 2007 are presented below[1].

Production:

Raw water supplied from River Göta älv, Lake Delsjön and Lake Rådasjön: 69 Mm^3

Maximum production capacity: Alelyckan 150,000 m^3/d
Lackarebäck 120,000 m^3/d

Delivery to the distribution network: 60.5 Mm^3 (in average 168,000 m^3 per day)

Four drinking water storage tanks at the plants, total volume: 52,000 m^3

Distribution:

Distribution network: 1,725 km

Pumping stations: 66

14 reservoirs, total volume: 64,165 m^3

Leakage: 19.1 m^3/(km day)

Water sales:

Within Göteborg city: 44.2 Mm^3

Outside Göteborg city: 3.4 Mm^3

Water price:

Fixed fee for residential houses: 1,645 SEK (€171[2])

Variable fee: 8.22 SEK/ m^3 (0.86[3] €/m^3)

Personnel:

Number of workers on a yearly basis, average: 251

Annual personnel costs: 117 MSEK (12.2[4] M€)

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[1] Göteborg Vatten (2008), www.goteborg.se/vatten, 2008-06-25
[2] Based on a exchange rate of 9.60 SEK/€
[3] Based on a exchange rate of 9.60 SEK/€
[4] Based on a exchange rate of 9.60 SEK/€