Use of Quantitative Microbial Risk Assessment (QMRA) as a Tool in the Hazard Analysis and Critical Control Point (HACCP) Management System for Water Treatment Plants - Especially for Development of Critical Limits

Rebecka Thorwaldsdotter

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Division of Ergonomics and Aerosol Technology
Department of Design Sciences
Faculty of Engineering
Lund University, Sweden

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Abstract: The primary objective for a drinking water supplier is to provide water that is safe for the public to drink and use. To improve process quality, it has been highlighted that a new approach is needed. A new risk based approach has been introduced by the World Health Organization. The recommended way to undertake risk assessment is by performing a Quantitative Microbial Risk Assessment (QMRA) whereas the risk management is proposed to rely on a management system named Water Safety Plan which includes the management system Hazard Analysis and Critical Control Point (HACCP) originating from the food industry. The overall purpose of this M.Sc. project is to evaluate and determine if and how QMRA can be used as a basis for an HACCP-style analysis in the water treatment industry. Focus is particularly on how to develop critical limits. The course of action was to perform a QMRA at a case plant. The choice of interesting issues to simulate was opted by the author after discussion with associates and in the light of HACCP. A simple model was created and simulations were made in an MS Excel program that was connected to Palisade @risk v.4.5 (@risk). The main conclusion was that a QMRA can be used as input to HACCP for water treatment plants (WTPs). Establishment of critical limits could be based on duration of process failure, on number of hazardous events and on incoming pathogen concentration. The performance of a QMRA will provide a better understanding of the whole WTP. However, at the moment there is a big limitation in existing data and there are also some differences between the food industry and the WTP that must be taken into account.

Institutionen för designvetenskaper
Ergonomi och aerosolteknologi
Lunds Tekniska Högskola
Box 118
SE-221 00 Lund
Sweden
http://www.eat.lth.se

Telefon: 046 - 222 80 18
Telefax: 046 - 222 44 31

The Department of Design Sciences
The Div. of Ergonomics and Aerosol Technology
Faculty of Engineering
Box 118
SE-221 00 Lund
Sweden
http://www.eat.lth.se/Default_Eng.htm
Telephone: +46 46 222 80 18
Fax: +46 46 222 44 31

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Summary

The primary objective for a drinking water supplier is to provide water that is safe for the public to drink and use. Microbiological safety is based upon the multiple barrier concept and the quality is maintained by protection of source water, application of treatment processes within the treatment plant and protection of the distribution system. To ensure that a water treatment process works properly, monitoring of different parameters such as pH, temperature, turbidity, alkalinity and indicator-bacteria are performed and compared to established standards.

To improve process quality, it has been highlighted that a new approach is needed. First of all, waterborne diseases have occurred even though standards have been fulfilled. Another objection for today's management is that the results from sampling often become available too late (after the water already has reached the consumer). An additional issue is the cost. In a community there are a lot of risks and costs for safety work. It is important to be efficient in the safety work and to direct resources to where they best will contribute to the overall risk reduction. Therefore an approach that can minimize the overall risk in the system is preferable.

A new risk based approach, the Safe Water Framework, has been introduced by the World Health Organization (WHO). The Safe Water Framework is an iterative methodology where risk assessments along with specified health targets constitute the basis for risk management.

The recommended way to undertake risk assessment is by performing a health-based Quantitative Microbial Risk Assessment (QMRA) whereas the risk management is proposed to rely on a management system named Water Safety Plan which includes the management system Hazard Analysis and Critical Control Point (HACCP).

HACCP is a widely used management system for controlling a variety of safety hazards within the food industry. It is a systematic method based on seven main principles, and it is from its origin a semi-quantitative method, i.e., judgement about the importance of a hazard and its probability to occur can be based on the opinion and experience of experts. Hazardous event is an important concept within HACCP. Hazardous event is an incident or situation that can contribute to the presence of a hazard. The seven principles of HACCP are:

1. Principle 1: Conduct a hazard analysis
2. Principle 2: Determine the critical control points (CCPs)
3. Principle 3: Establish critical limits
4. Principle 4: Establish monitoring procedures
5. Principle 5: Establish corrective actions (if the critical limit is exceeded)
6. Principle 6: Establish verification procedures
7. Principle 7: Establish record-keeping and documentation procedures

The overall purpose of this M.Sc. project is to evaluate and determine if and how QMRA can be used as a basis for an HACCP-style analysis in the water treatment industry. The aim is to describe how the three first HACCP-principles can be performed at a water treatment plant when results from a QMRA are used. Focus is particularly on how to develop critical limits.

The course of action was to perform a QMRA at a case plant. Lackarebäck Water Treatment Plant (LWTP) located in Gothenburg, Sweden, was used for the case study. A simple model of the treatment plant was created in MS Excel. The input was pathogen concentration in the water upstream the treatment process and the model was calculating the concentration of pathogens downstream. By assessing the average water consumption per customer and combining the results with dose-response relationships, pathogen exposure could be related to health outcomes. Results from simulations were presented as infection risk and annual infection risk. Annual infection risk gives the answer to how many infections per 10 000 persons and year that can be expected from each pathogen. To be able to assess the infection risks obtained from the simulations the Dutch Drinking Water Degree required level of safety was consistently used as a reference. This says that one infection per 10 000 persons and year is the acceptable level.

The choice of interesting issues to simulate and the way of action when critical limits should be established was opted by the author after discussion with associates and in the light of HACCP. The results were then tested for how well they fit into the first three principles of HACCP.

Main issues in the case study were:

- Infection risk under normal conditions - base line scenario
- Critical incoming concentration under base line conditions
- Additional infection risk for hazardous events
- Infection risk versus duration of failure
- Sensitivity analysis

Simulations were made in an MS Excel program that was connected to Palisade @risk v.4.5 (@risk). @risk makes it possible to use distribution functions instead of point values and the results can be presented with an arbitrary percentile. If nothing else is stated the 95-percentile was used. Three pathogens were used as index organisms: *Cryptosporidium,* Norovirus and *Campylobacter.*

The main conclusion was that a QMRA can be used as input to HACCP for water treatment plants. However, there are some differences between the food industry and the WTP and they must be taken into account. One example of this is the initial product. Within the food industry microbial contamination is expected to occur somewhere within the walls of the industry. For WTP the pathogens are already present when the raw water enters the plant.

The simulated infection risk from a QMRA could provide the analysis with information about which pathogen that must be prioritized and which pathogen that should be involved in the HACCP performance, which corresponds to HACCP-principle 1.

As a starting point when making a judgement about CCP (HACCP-principle 2) the suggested approach was to use each treatment step within the water treatment plant as important control points and also to involve the point where the incoming water is entering the plant.

Pathogen concentration was suggested as one basis for the establishment of critical limits (HACCP-principle 3). Other suggestions were to use simulations of hazardous events and process failures. By performing hazardous event simulations the additional infection risk could be calculated for each hazardous event. These results give good information about which hazardous events that have to be prioritized and how many of these events that can be tolerated before the level of acceptable infections is exceeded. Graphs with infection risk plotted against duration of failure can work as a basis for judgment about how long time a failure can be tolerated before the level of acceptable infection is exceeded.

In the analysis of QMRA performance it was stated that performance of a QMRA will provide a better understanding of the whole WTP. It will lead to identification of actual barriers and better understanding about lack of knowledge. It will also lead to learning about new scenarios and events. At the moment there is a big limitation in existing data.

The main issue when performing the simulations was the choice of data. It was very difficult to find and/or to know what kind of data to use. With all of the data, there were associated uncertainties and high variability. However, the results of this study have shown that output from a QMRA can provide knowledge of the plant that can be used in the management of a WTP. By collecting all of the data in a data system it is easy to improve the model and update simulations gradually when better data are received.

The fact that a specific WTP was used for a case study does not have any effect on the suggestion on how QMRA should be used with the first three principles of HACCP. The performance should be the same for each water treatment plant.

It should be remembered that the suggestions about HACCP performance made in this project are not to be considered as complete. More work has to be done in order to gain experience and widen the knowledge.

Finally it was stated that an additional use of this project is that it can act as a basis for further discussions of HACCP-principles within the water treatment plan.

Sammanfattning

Det primära målet för en dricksvattenproducent är att tillgodose konsumenten med vatten som är säkert att dricka och använda. Mikrobiell säkerhet baseras på konceptet med multipla barriärer och kvaliteten upprätthålls genom skydd av dricksvattentäkter, applicering av behandlingsprocesser inom vattenverket samt skydd av distributionssystemet. För att försäkra sig om att en behandlingsprocess fungerar som den ska övervakas olika parametrar så som pH, temperatur, grumlighet, alkalitet och indikatorbakterier som sedan jämförs med fastställda standarder.

För att förbättra kvaliteten på processarbetet i vattenverk så har ett nytt tillvägagångssätt efterfrågats. Detta eftersom det förekommer vattenburna sjukdomar även om gällande standard har uppfyllts. En annan invändning mot dagens handhavande är att resultaten från provtagningar ofta blir tillgängliga först efter det att vattnet har nått konsumenten. En tredje parameter är kostnadsfrågan. I ett samhälle finns det en rad olika risker och kostnader för säkerhetsarbete. Det är viktigt att vara effektiv i säkerhetsarbetet och lägga resurserna där de kan bidra till störst riskreduktion. Därför är ett tillvägagångssätt som kan minimera den totala risken i ett system att föredra.

En ny riskbaserad ansats, the Safe Water Framework, har introducerats av Världshälsoorganisationen (WHO). The Safe Water Framework är en iterativ metodik där riskbedömning och specificerade hälsomål skall utgöra grunden för riskhanteringsprocessen.

Det föreslagna sättet för att utföra en riskbedömning är genom en hälsobaserad QMRA (Quantitative Microbial Risk Assessment) medan riskhanteringsprocessen kommer att bygga på ledningssystemet the Water Safety Plan vilket inkluderar HACCP (Hazard Analysis and Critical Control Point).

HACCP är ett ledningssystem som i stor utsträckning används inom livsmedelsindustrin för att kontrollera en rad olika säkerhetsrisker. Det är en systematisk metod som baseras på sju grundprinciper där bedömning av risker ofta sker semikvantitativt. Med detta menas att bedömningen av en faras betydelse och dess sannolikhet att inträffa kan baseras på experters åsikter och erfarenheter. Farlig händelse är ett viktigt begrepp inom HACCP. Farlig händelse är en incident eller situation som kan bidra till uppkomsten av en fara. HACCPs sju principer är:

1. Princip 1: Utföra en faroanalys
2. Princip 2: Identifiera de kritiska styrpunkterna (CCPs)
3. Princip 3: Fastställa kritiska gränsvärden
4. Princip 4: Upprätta system för övervakning
5. Princip 5: Fastställa korrigerande åtgärder
6. Princip 6: Upprätta rutiner för verifiering
7. Princip 7: Upprätta dokumentationsrutiner

Syftet med detta examensarbete är att utvärdera och bestämma om och hur QMRA kan användas som grund för HACCP inom vattenverk. Målet är att beskriva hur de tre första HACCP-principerna kan utföras vid ett vattenverk när resultat från en QMRA används. Fokus är särskilt på hur kritiska gränsvärden ska tas fram.

Tillvägagångssättet var att utföra en QMRA på ett vattenverk. Lackarebäck vattenverk i Göteborg, Sverige användes som fallstudie. En enkel modell av vattenverket skapades i MS Excel. Patogenkoncentrationen i vattnet uppströms reningsstegen användes som indata och modellen beräknade sedan patogenkoncentrationen nedströms. Genom att bedöma medelkonsumtionen per person kombinerat med beräkningsresultaten och sätta in detta i ett dos-responssamband kunde patogenexponering relateras till hälsa. Resultaten från simuleringarna presenterades som infektionsrisk och årlig infektionsrisk. Den årliga infektionsrisken svarar på hur många infektioner som förväntas uppstå per 10 000 personer och år för varje simulerad patogen. För att kunna göra en bedömning av betydelsen av de simulerade infektionsriskerna användes den krävda säkerhetsnivån från ”the Dutch Drinking Water Degree” som referens. Denna säger att en infektion per 10 000 personer och år är acceptabelt.

Valet av intressanta parametrar att simulera och tillvägagångssätt för hur kritiska gränsvärden skall bestämmas utfördes av författaren i samråd med kollegor och med HACCP i åtanke. Resultaten testades sedan för hur väl de passade in i HACCPs tre första principer.

Huvudparametrar att simulera i fallstudien:

- Infektionsrisk vid normala förhållanden - ursprungsscenario
- Kritisk inkommande koncentration vid ursprungsförhållande
- Ökad infektionsrisk vid farliga händelser
- Infektionsrisk som funktion av tid för systemfel i reningsprocessen
- Känslighetsanalys

Simuleringarna utfördes i ett MS Excel-program som var kopplat till Palisade @risk v.4.5 (@risk). @risk gör det möjligt att använda fördelningsfunktioner istället för enstaka punktvärden och resultaten kan presenteras med en vald percentil. Om inget annat anges så användes 95-percentilen. Tre olika patogener användes som indexorganismer: *Cryptosporidium,* Norovirus och *Campylobacter*.

Slutsatsen var att resultat från en QMRA kan användas som indata till HACCP på ett vattenverk. Det finns dock olikheter mellan livsmedelindustrin och vattenverk som måste beaktas.

Den simulerade infektionsrisken från en QMRA kan tillgodose analysen med information om vilken patogen som måste prioriteras och vilken patogen som borde involveras i HACCP-utförandet. Detta är i linje med HACCP-princip 1.

Det föreslagna tillvägagångssättet vid bedömning av kritiska kontrollpunkter (CCP) var att använda varje reningsteg inom vattenverket som viktiga kontrollpunkter samt att även ta med punkten där råvattnet kommer in i vattenverket. Detta är i linje med HACCP-princip 2.

Patogenkoncentration föreslogs som en grund för fastställande av kritiska gränsvärden (HACCP-princip 3). Ett annat förslag var att använda simuleringar för händelser och

systemfel i reningsprocessen. Genom att simulera olika farliga händelser fås den ökade infektionsrisken fram. Dessa resultat ger bra information om vilka farliga händelser som måste prioriteras och hur många av dessa som kan tolereras innan tillåten infektionsnivå överskrids. Diagram med infektionsrisk plottad som funktion av tid för systemfel i reningsprocessen kan fungera som en grund för fastställande av hur lång tid ett systemfel kan tillåtas pågå innan tillåten infektionsnivå överskrids.

I utvärderingen fastslogs det att utförandet av en QMRA ökar förståelsen för hela processen i vattenverket. Den identifierar faktiska barriärer och ökar medvetandet om kunskapsbrister. Den leder också till kunskap om nya tänkbara scenarier och händelser. Det fastslogs också att det för tillfället finns stora begränsningar i tillgänglig data.

Valet av data var en av de stora utmaningarna vid utförandet av simuleringarna. Det var väldigt svårt att hitta och/eller veta vilken data som skulle användas. All data medförde osäkerheter och stora variationer. Trots detta har resultaten från detta arbete visat att utdata från en QMRA kan ge kunskap som kan användas för ledning och drift av ett vattenverk. Genom att samla in all data i ett datasystem blir det lätt att förbättra modellen och gradvis uppdatera simuleringar när bättre data blir tillgänglig.

Det faktum att fallstudien utfördes på ett specifik vattenverk har ingen inverkan på förslaget om hur QMRA bör användas med HACCPs tre första principer. Utförandet borde bli det samma oavsett vilket vattenverk som tas i beaktning.

Det ska understrykas att förslagen om utförandet av HACCP som gjordes i detta arbete inte ska ses som kompletta. För att få mer erfarenhet och utöka kunskapen måste mer arbete utföras.

Slutligen fastslogs det att ett ytterligare användningsområde för detta examensarbete är att det kan fungera som grund för fortsatt diskussion kring användandet av HACCP-principerna inom vattenverk.

Contents

Abbreviations and Glossary

For definitions used within the HACCP-principles, see section 2.8.

ALWP	Alelyckan Water Treatment Plant
CCP	Critical Control Point
CL	Critical Limit
CP	Control Point
CSTR	Continuous Stirred Tank Reactor
Ct-concept	Ct-concept is used within the disinfection step. The concentration of the disinfectant multiplied with the time that the disinfectant is in contact with the water will result in a Ct-value.
CTSs	Catchment to Tap Systems
DEC	Decimal Elimination Capacity. One way to describe the inactivation of pathogens.
GAC	Granulated Activated Carbon (Filtration method)
HACCP	Hazard Analysis and Critical Control Point. A system that identifies, evaluates and controls hazards.
Hazard	*"Hazards are biological, chemical, physical or radiological agent that have the potential to cause harm and/or can give rise to water quality which is unacceptable for consumers."* (Nadebaum *et al.*, 2004)
LWTP	Lackarebäck Water Treatment Plant, which is the case plant for the case study.
MEC	Microorganism Elimination Credit.
Microrisk	Microrisk is a European Commission funded research project
Monitoring	*"The act of conducting a planned series of observations or measurements of operational and/or critical limits to assess whether a control point is under control."* (Medema & Smeets, 2004)
Pathogen	*"A pathogen is a microorganism capable of causing disease."* (Medema & Smeets, 2004)
QMRA	Quantitative Microbial Risk Assessment
Risk	*"Risk is the likelihood of identified hazards causing harm in exposed populations in a specified timeframe, including the magnitude of that harm and/or the consequences."* (WHO, 2005)
WSP	Water Safety Plan. Water Safety Plan is a management system that supports a systematic way of identifying, evaluating and controlling hazards in drinking water production.
WTP	Water treatment plant

1 Introduction

This chapter gives the reader a short background to why this project was performed. The objective and the course of action are presented as well as the structure of the report. Project boundaries are also stated.

1.1 Background

The primary objective for a drinking water supplier is to provide water that is safe for the public to drink and use. The water treatment industry has a long history of drinking water production that goes back a century. But even if water treatment plants (WTPs) have a proven capability, outbreaks of waterborne diseases still occur in developing as well as in developed countries. This is a very important issue since water is used daily by all humans. It is long proven that pathogenic microorganisms in drinking water can cause serious illness or even death (Medema & Smeets, 2004). Hence, strategies to improve water quality can be expected to deliver substantial health gains (WHO, 2005).

The traditional way to control and manage the microbiological quality issue is by monitoring indicators and surrogates and by responding when a parameter value moves outside its target range. Parameters monitored include flow, turbidity, pH, disinfectant residuals and temperature. The monitoring is made at several points within the treatment process and if limits and targets are not achieved, remedial action must be taken (Roser, 2006). Although these measures of the process performance can not be directly translated into pathogen removal, they still can prove to be a valuable source of information for undertaking assessment of risk. Water quality measurements are also carried out after the water has reached the consumers on follow up samples or in response to complaints (VA-verket, 2005).

Traditionally critical limits for pathogens have not been set from estimated risk. Rather they have been based on surrogate and microbial indicator measurement values which are seen as acceptable by experts and the public. In the case of the public a tasteless product lacking visible turbidity is usually acceptable. For water quality managers the lack of indicator bacteria in 100 ml water samples has been the key measure to decide if the water quality is acceptable. (Roser, 2006)

This approach can be seen to have worked well as the incidence of water borne disease in developed countries is low. However, outbreaks of waterborne diseases have occurred even though measuring and monitoring standards have been fulfilled. Results from sampling often become available too late for timely action (i.e., after that the water already has reached the consumer) (Medema & Smeets, 2004).

Cost-effectiveness is another consideration. In a community there are a lot of risks and costs for safety work. It is important to be efficient in the safety work and put the money where it will have the best overall risk reduction. An approach that can minimize the overall risk in the system is to prefer. As a result of the limitations in traditional water management (as mentioned earlier) a new approach is needed. (Microrisk, 2005)

A new risk based approach, the Safe Water Framework, has been introduced by the World Health Organisation (WHO) as a new strategy for provision of water that is safe to drink. The Safe Water Framework is an iterative methodology where risk assessments along with specified health targets constitute the basis for risk management. (Fewtrell & Bartram, 2001)

A Water Safety Plan (WSP) can work as a guide for the water treatment industry to control and manage their safety work (WHO, 2005; Medema & Smeets, 2004). A management system can help the industry to see the most important issues, learn more about their own system and help the plant to keep the safety work updated.

Within the food industry there is a widely used management system for controlling safety hazards called Hazard Analysis and Critical Control Point (HACCP) (NACMCF, 1997). It is a systematic method based on seven main principles to assure quality and systematic management. The seven principles are (NACMCF, 1997):

1. Principle 1: Conduct a hazard analysis
2. Principle 2: Determine the critical control points (CCPs)
3. Principle 3: Establish critical limits
4. Principle 4: Establish monitoring procedures
5. Principle 5: Establish corrective actions (if the critical limit is exceeded)
6. Principle 6: Establish verification procedures
7. Principle 7: Establish record-keeping and documentation procedures

From its origin the HACCP is a semi-quantitative method, i.e., judgement about the importance of hazards is based on the opinion and the experience of experts. Critical control points (CCPs) and critical limits are two important concepts in this framework and the food industry have developed methods for choosing CCPs and establishing critical limits.

WHO has since 1984 published guidelines for drinking water quality and has now proposed that HACCP should be included as a part of the proposed Water Safety Plan (WSP) (WHO, 2005). The rational of HACCP is to control hazards at the time of manufacture rather than trying to detect problems by testing the end product. WHO (2004) has also proposed that a health-based Quantitative Microbial Risk Assessment (QMRA) could be used as a base for the HACCP performance. The objective of QMRA is to identify and quantify the risk of infections. This method should provide the WTP with quantitative scientifically underpinned data about the importance of hazards based on health target. The approach would use a risk management approach to reduce the overall risk in the system instead of using surrogates and indicators (Havelaar, 1994; Medema & Smeets, 2004). At the moment there exist no established methods on how to implement the outcome from a QMRA into HACCP.

Most work performed within the water supply industry already involves the application of HACCP-principles but it tends not to be performed in a systematic manner. A significant obstacle has been a lack of information of how to operationally apply the principles in an efficient way as the existing guidelines for HACCP applications are largely generic and conceptual. “How many CCPs are reasonable for the WTP (a couple or several)?” and “How can critical limits be established?” are examples of unfulfilled issues. (Roser, 2006)
The Swedish Water & Wastewater Association (2006) has given attentions to the lack of working methods and established a working team to produce a framework for HACCP

application within water supply systems in Sweden. Their internet based framework is available at (www.svensktvatten.se) and is continuously updated.

To be able to better integrate QMRA and HACCP there is a need for further research. Microrisk is a European Commission funded research project which has among others the objective of better integrating QMRA and HACCP for use in WSPs. The project consists of eight work packages, and will result in a final harmonized risk assessment framework (Microrisk, 2006). Two areas in this work are the detection and the evaluation of risk. Event detection through Supervisory Control and Data Acquisition (SCADA) data has been evaluated in the M.Sc. degree project "The Use of Water Treatment SCADA Data to Quantify Hazardous Microbiological Events and Risks Arising - A Case Study from Sweden" (Nilsson, 2006).

This project has focussed on the evaluation of risk and has been undertaken in close relation with work package 6 in Microrisk and to the M.Sc. degree project mentioned earlier. Therefore the same or similar ideas or results may be presented in each of the above reports. Some results from SCADA evaluation were used as inputs for simulations in this project, they are found in section 2.7.2. Some background data that were valid for both reports have been worked on in collaboration and are therefore presented in a similar or identical fashion in both projects. Identical sections are marked with an asterix (*) in the beginning of that section or chapter. "The Use of Water Treatment SCADA Data to Quantify Hazardous Microbiological Events and Risks Arising - A Case Study from Sweden" (Nilsson, 2006) is denominated as the associated project.

1.2 Objectives

The overall purpose of this M.Sc. project is to evaluate and determine if and how QMRA can be used as a basis for an HACCP-style analysis in the water treatment industry. The aim is to describe how the three first HACCP-principles can be performed at a water treatment plant when results from a QMRA are used. Focus is particularly on how to develop critical limits.

1.3 Method

The way of undertaking this project is to perform a QMRA on a selected water treatment plant, see chapter 5 for case plant description. A simple model of the treatment plant is created in MS Excel. The results from the simulations (the risk probability estimates) are then used as input for the three first HACCP-principles. The choice of interesting issues to simulate and way of action when critical limits should be established is opted by the author after discussion with associates within work package 6 in Microrisk and in the light of HACCP. These issues are presented in chapter 4. The results are tested for how well they fit into the first three principles of HACCP. The QMRA is performed as a case study and Lackarebäck Water Treatment Plant (LWTP) in Gothenburg is used as case plant. LWTP is involved in the Microrisk project and offers sufficient good background data for simulations and is therefore used. Three pathogens are used as index organisms: *Cryptosporidium,* Norovirus and *Campylobacter.* These organisms are among those already selected for consideration in Microrisk and are therefore used in this project as well. A literature review is performed to provide the author with enough theory and data so that the case study can be performed.

1.4 Structure of the Report

- Part One - Literature Review
- Part Two - Case Study
- Part Three - Results and Discussion

Part One - Literature Review (chapter 1 - 4) covers the WHO (2005) Drinking Water Guidelines and Harmonized Framework, HACCP and its principles, as well as the different aspects of a QMRA. Other topics covered are water treatment, hazards and SCADA monitoring. The relationship between QMRA and HACCP is shortly described. All contents of a QMRA are treated in this section so that the performance in Part Two (Case Study) will appear more obvious. The last chapter in this part presents the issues used for the simulations in the Case Study. Each chapter is introduced with a brief summary discussing the connection to the overall project objectives.

Part Two - Case Study (chapter 5 - 8) is the part where the QMRA is performed. This section introduces the case plant Lackarebäck Water Treatment Plant (LWTP), describes the method used and presents results from the case study. The results are presented as "Results from QMRA". The last section in this chapter "Case Study Analysis" emphasizes the differences between the food and water industry but also presents an analysis of the QMRA performance.

Part Three - Results and Discussion (chapter 9 - 10) is the final part in this project. The outcome from the case study is used to develop the suggestions of how the three HACCP-principles could be performed and how critical limits can be established. Part Three ends with an overall discussion about the project.

1.5 Project Boundaries

The method of the study was to perform a QMRA for LWTP. Risks arising in the catchment area and in the distribution system were considered to be beyond the scope of the project. For time and resource reasons the attention was focused on the first three of the in total seven principles of HACCP. It might be possible to use QMRA for the last four principles. This matter was however beyond the scope of the project and was therefore not further investigated. Finally the project only focussed on microbial hazards.

Part 1 - Literature Review

2 Water Treatment Management

This chapter provides an introduction to the proposed improvements for the water work. The World Health Organizations proposed Water Safety Plans and the adoption of the Hazard Analysis and Critical Control Point (HACCP) management system are introduced. The concept of Quantitative Microbial Risk Assessment (QMRA) and HACCP performance are described. Concepts such as hazardous event and SCADA-data are introduced. Section 2.2 addresses WHO and its Safety Water Framework. The section has been written to provide a background for the two associated projects and is therefore very similar in both reports. Also, parts of the descriptions of the framework for assessing microbial risk for drinking water are similar.

*2.1 World Health Organization Framework**

Since 1984 The World Health Organization (WHO) has published "Guidelines for Drinking-water Quality". The guidelines are continuously edited and updated and act as a starting point for the setting of water quality standards worldwide (WHO, 2005).

WHO has stated the need for a harmonized framework that integrates risk assessment and risk management. The risk that should be managed and assessed is the one of being exposed and infected by pathogens when consuming water. WHO advocates that a risk based on an iterative approach with embedded quality targets should be used (Fewtrell & Bartram, 2001). As the prerequisites are likely to change, risk assessment and risk management is an ongoing iterative process. The framework, named Safe Water Framework, is depicted in Figure 1.

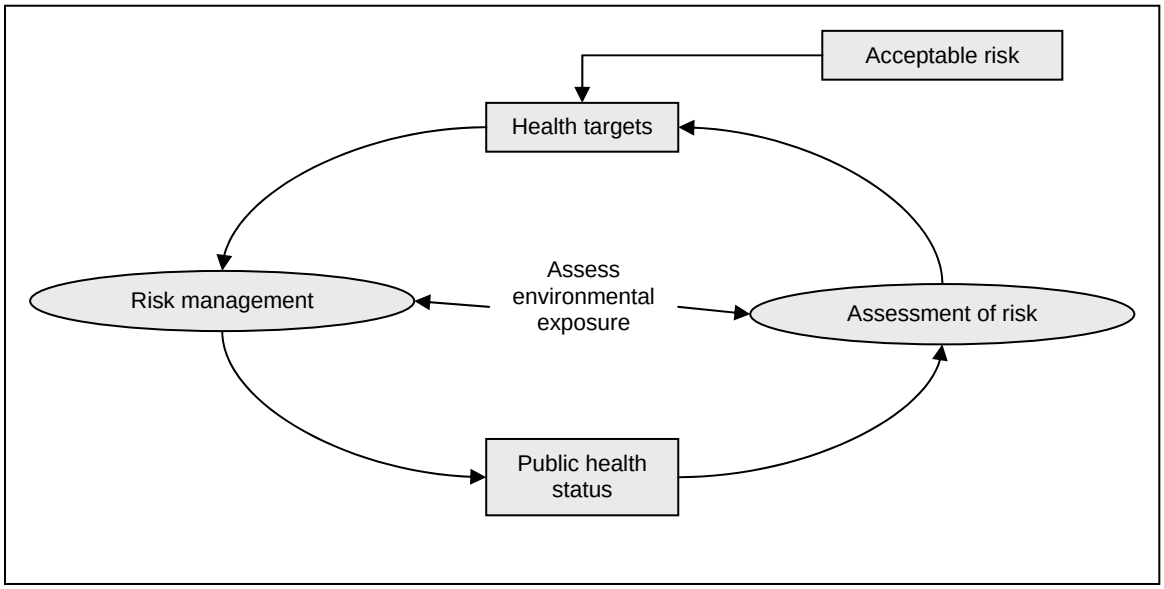

*Figure 1. Safe Water Framework (Fewtrell & Bartram, 2001)**

2.1.1 Risk assessment

For WHO (2005) guidelines, the emphasis is upon health and, as such, the assessment of risk is an assessment of health risks. The assessment aims to state the risk of disease and/or the risk of infection. The assessment of risk is a starting point for the harmonized framework and the overall purpose with the risk assessment is to act as a basis for decision making, i.e., risk management. (Fewtrell & Bartram, 2001)

2.1.2 Assess environmental exposure

Assessment of environmental exposure is a formal component in risk assessment and, an important input to the risk management. The role environmental exposure assessment plays in risk management constitutes of prioritizing among potential interventions. For example, if the pathogen exposure mainly occurs via a non-water related source, it might be of no or insignificant benefit trying to further prevent infections through drinking water. (Fewtrell & Bartram, 2001)

2.1.3 Acceptable risk and health target

Acceptable risk and the outcome of assessment of risk underlies specified health targets. In its Guidelines for Drinking-water Quality, WHO (1993) suggests:

The judgment of safety - or what is an acceptable level of risk - is a matter in which society as a whole has a role to play. The final judgment as to whether the benefit resulting from the adoption of any of the guideline values… justifies the cost is for each country to decide.

Hence, acceptable risk is a matter of cost-benefit where the health targets must be sensible and achievable.

There exists no single definition of acceptable risk that can be applied all over the world. Therefore every single country has to make its own judgment about what risks that can be accepted. A proposed and to a great extent used health target is that less than one person in 10 000 per year should become infected by drinking water (Fewtrell & Bartram, 2001). This is the safety that is required from the Dutch Drinking Water Degree (Hijnen *et al*., 2005).

2.1.4 Risk management

Based on the specified health targets, water quality targets are defined, implemented and monitored. In cases where direct monitoring is not possible, indirect methods such as process performance and source water data can be used to ensure that the target values are achieved. The emphasis should be on monitoring systems that have the ability to rapidly and frequently inform the management of any deviations on an appropriate time scale. It has been proposed that the management system should be based upon the existing HACCP management system used in the food industry. (Fewtrell & Bartram, 2001)

2.1.5 Public health status

To ensure that the measures being put into place are having the desired effect, a survey of the public health must be undertaken. The public health outcome is the confirmation that the quality targets defined during the risk management process are adequate. Measuring the public health status should not be seen as an endpoint or solution, but rather as a basis for continuing with further risk assessments. (Fewtrell & Bartram, 2001)

2.2 Water Safety Plan

By developing and using a Water Safety Plan (WSP), the management of a water treatment plant (WTP) should become more systematic, easier to maintain and operate. WHO (2005) has proposed that a WSP consist of three main components: System Assessment, Operational Monitoring and Management Plans, Documentation and Communication (see Figure 2). The figure also shows where the HACCP-method fits into the WSP.

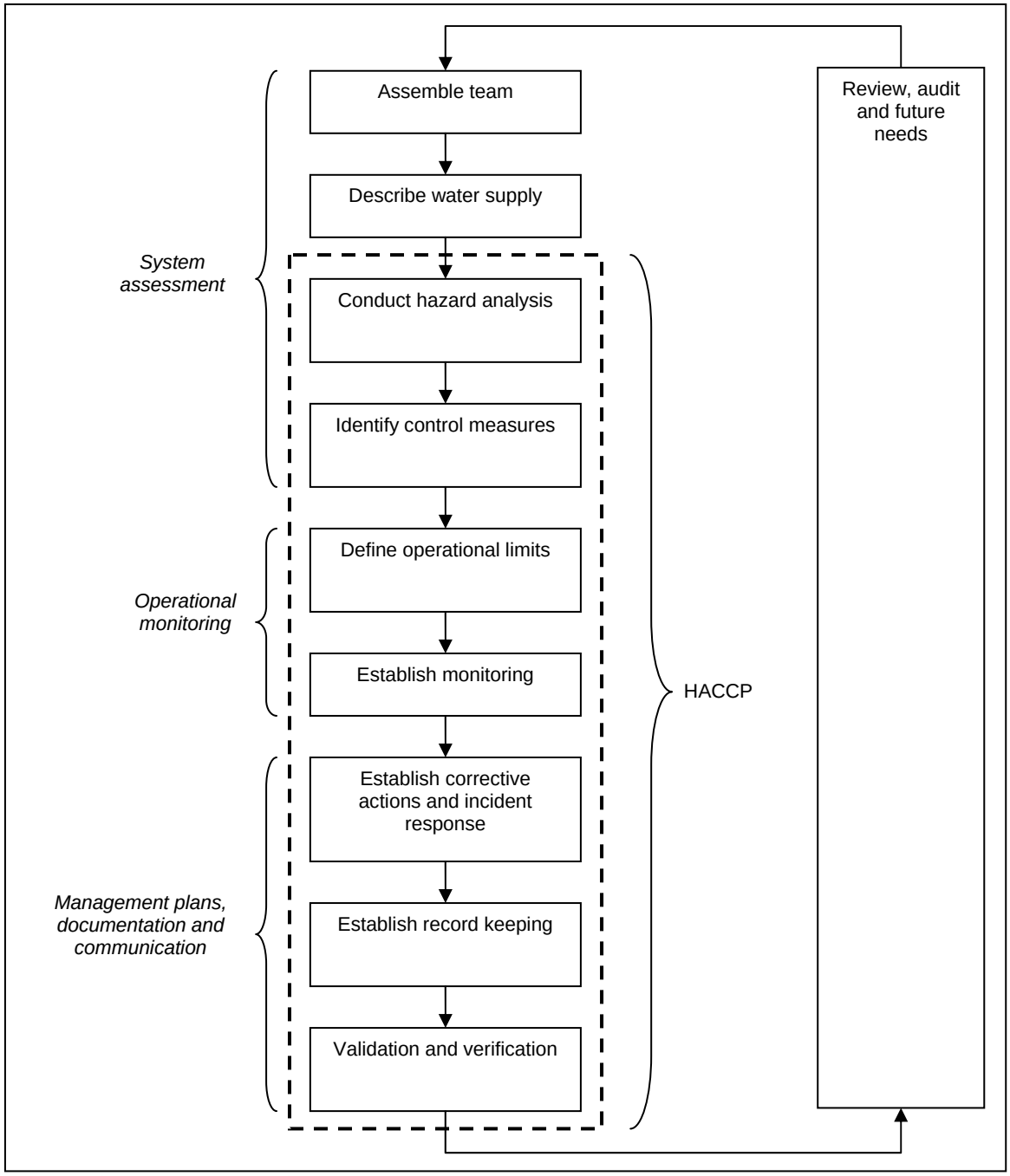

*Figure 2. The components of the Water Safety Plan (WHO, 2005)**

2.3 HACCP

Hazard Analysis and Critical Control Point (HACCP) is a systematic method to assure quality and systematic management. For decades it has been a well known and well used management system within the food industry.

The method is built upon identification within the process of each step that can be crucial regarding safety, finding critical control points, and thereafter managing by using this control points for reducing the risk. (NACMCF, 1997)

2.3.1 Hazard and hazardous events

Hazard in this context is a microorganism that potentially can cause a health effect. One definition of the word hazard that is used for the WTP says:
"Hazards are biological, chemical, physical or radiological agent that have the potential to cause harm and/or can give rise to water quality which is unacceptable for consumers." (Nadebaum *et al.,* 2004).

"Hazardous events are those incidents or situations that can contribute to the presence of a hazard." (Nadebaum *et al.,* 2004)

As the definition indicates an event is a situation or occurrence that contributes to the presence of a microorganism (hazard). All events are not necessarily hazardous events but in this project the expression event and hazardous event will be used as synonyms. Events can be such as low disinfection dose at the disinfection stage, wrong pH, rainfall, wrong coagulant etc. It is not the event itself that causes harm. Rather the event is the trigger that can contribute to the presence of a hazard. For example a hazardous event can make the pathogen concentration to which consumers are exposed higher than normal.

2.3.2 HACCP and the seven principles

HACCP is based upon seven principles (NACMCF, 1997):

1. Principle 1: Conduct a hazard analysis
2. Principle 2: Determine the critical control points (CCPs)
3. Principle 3: Establish critical limits
4. Principle 4: Establish monitoring procedures
5. Principle 5: Establish corrective actions (if the critical limit is exceeded)
6. Principle 6: Establish verification procedures
7. Principle 7: Establish record-keeping and documentation procedures

To manage and perform an HACCP it is necessary to undertake some preparatory activities which involve assembly of a HACCP team and description of the product. These preparation steps are involved in the WHO water safety plan as shown in Figure 2. See Table 1 for further description of the HACCP-principles. This table summarizes information about HACCP found both from the food industry and from what is written for the water treatment industry. Since this project focuses on the fist three principles the last four are just briefly described.

Table 1. Presentation of the seven HACCP-principles. Literature sources: (NACMCF, 1997) (Swedish Water & Wastwater Association, 2006) (Havelaar, 1994) (Nadebaum et al., 2004).

Principle 1: Conduct a hazard analysis The hazard analysis is a way to identify hazards and assess their importance. A hazard is in this context a microorganism. The purpose is to develop a list of hazards, which is of such significance that they can cause injury or illness if not effectively controlled. Possibilities of

preventing or removing the hazard should be analysed. If the hazards are not likely to occur, there is no use of further HACCP-investigation. Some HACCP documents require possible control measures for each hazard. In the water treatment industry more then one control measure may be required to control a specific hazard and more the one hazard may be controlled by a specified measure.

There are different methods to identify hazards. Information about hazards can come from different sources such as: outbreak data, laboratory studies or expert group's opinion.

The National Advisory Committee on Microbiological Criteria for Foods (1997) divides the hazard analysis into two stages. The first stage is the hazard identification, and the second stage is the hazard evaluation. In the second stage each potential hazard is evaluated based on severity and likelihood. Likelihood is usually based on a combination of epidemiological data, information in technical literature and experience. The result from multiplying the likelihood of occurrence and severity is a value that can be used as a base for the risk assessment; the risk is often presented in risk matrices or as a risk scale. Likelihood and severity are based on expert opinion (semi-quantitative, see section 2.4) such as "big" or "small" that is translated to a scale for example from 1 to 5.

In the framework from Swedish Water & Wastewater Association (2006) the hazard evaluation is placed under Principle 2.

"A Guide to Hazard Identification & Risk Assessment for Water Supplies" is a developed framework that can be used as a help for identification and evaluation of hazards within the water supplies systems.

Principle 2: Determine the critical control points (CCPs)
A Critical Control Point (CCP) is a point in the process that is an essential point or process for the (water/food) quality and the management performance. It is essential to perform a proper identification of the CCP because major effort in management will be directed towards these stages. The most common way to identify a CCP is to use a decision tree. The decision tree is a well known procedure and is used in the food industry but has also been adopted into the water industry. The tree should be used as a tool for CCP identification but is not a substitute for expert knowledge. If a decision tree is used to identify a CCP the general way of action is that a control point is not a CCP (for a certain hazard) if there is a later step in the process that can prevent or reduce the hazard.

One definition for CCP from the food industry is: *"A step at which control can be applied and is essential to prevent or eliminate a food safety hazard or reduce it to an acceptable level."* (NACMCF, 1997)
For additional definitions see section 2.8.

Principle 3: Establish critical limits
Critical limits should be established for each CCP. It can be different levels such as attentive, alarm and/or action levels.

One definition for critical limits from the food industry is: *"A maximum and/or minimum value to which a biological, chemical or physical parameter must be controlled at a CCP in order to prevent, eliminate or reduce the parameter to an acceptable level in the occurrence of a food safety hazard."* (NACMCF, 1997)

For additional definitions see section 2.8.
Principle 4: Establish monitoring procedures
Surveillance is necessary and it is proposed that the industry could have an online monitoring system with direct alarm functions. See section 2.7.1 for more online monitoring systems (SCADA). Apart from monitoring for direct notice in process failure the monitoring can be used for providing documentation of the process for later verification and for deterring loss of control.

Principle 5: Establish corrective actions
There should be descriptions on how to attend to an alarm or attentive levels. Routines for action, for what to do and by whom, must be established.

Principle 6: Establish verification procedures
There must be methods established for verification, i.e., a system for evaluating that the HACCP system works according to the HACCP plan.

Principle 7: Establish record-keeping and documentation procedures
Routines for maintaining documentation, its performance and where it should be kept must be established.

2.4 Tier of Risk Assessment

An analysis of risk can be undertaken at three different levels (Nilsson, 2000):

Qualitative method - used mainly to identify hazards or to compare risks. The risk is described in words such as “big” or “small”.

Semi-quantitative method - is more detailed than the qualitative analyses and values are given to consequences and probabilities (they do not have to be exact). Achieved results are often presented in matrices or in ranking scales.

Quantitative method - this is the complete numerical method. Its performance varies depending on the risks being assessed. All-embracing is that uncertainty in data must be taken into account when calculating. Quantitative Risk Assessment (QRA) is a method to quantify risk within a system that can affect humans.

*2.5 Quantitative Microbial Risk Assessment (QMRA)**

Quantitative Microbial Risk Assessment (QMRA) is a way to quantify microbial risk within a system and its effect on humans. This is the proposed method to undertake assessment of risk in the WHO harmonized framework (Medema & Smeets, 2004). QMRA is based on a logical chain of five steps, see Figure 3.

As a last step in the QMRA a characterization of the risk is performed. Exposure that is entered into a dose-response relation results in an estimation of infection risk often expressed as the probability of infection per person per year or per day. This can be made as simple point estimation or be performed with Monte Carlo simulations so that distribution functions and uncertainty can be taken into account.

Risk estimates can be used for controlling a system's performance and its capacity to fulfill established health targets and as a tool for prioritizing risks. The results are scientifically based, transparent and objective. (Medema & Smeets, 2004)

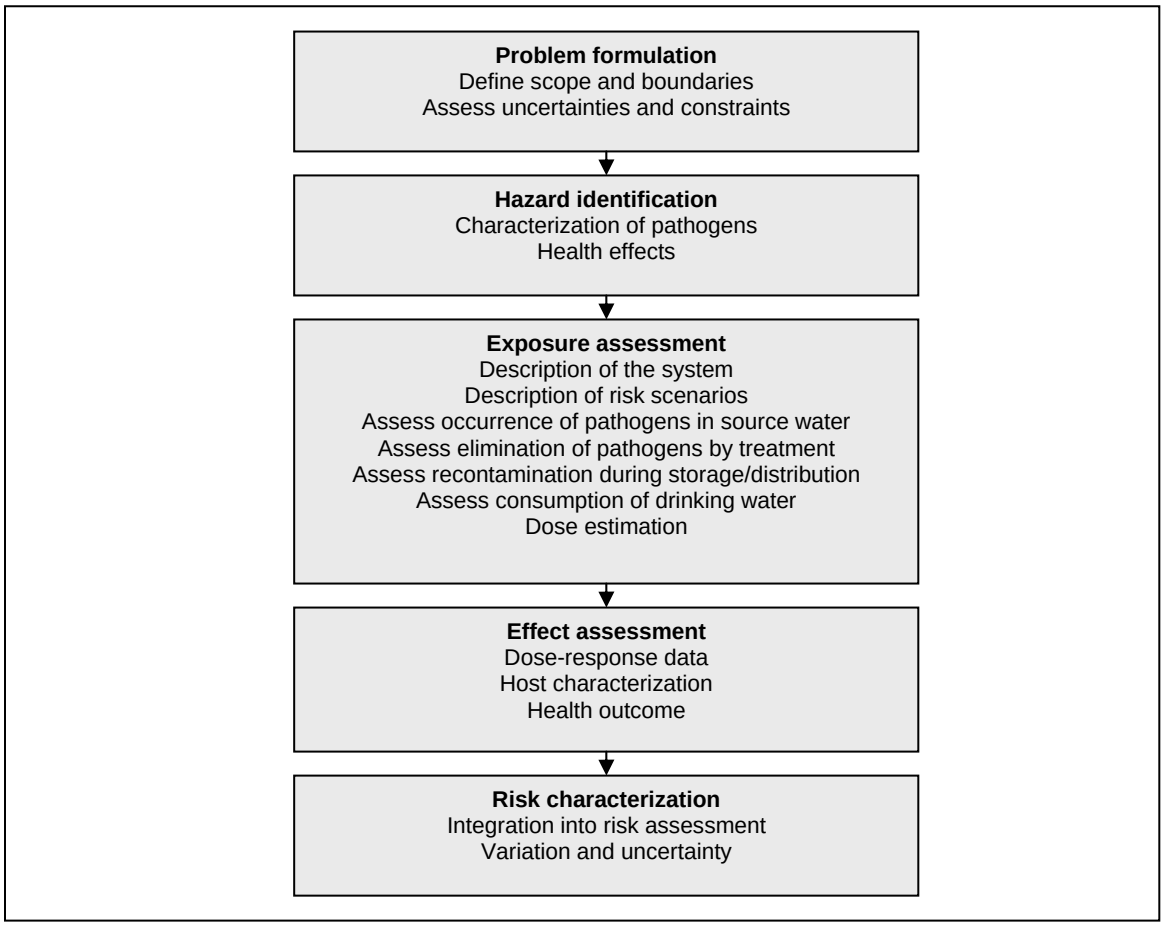

*Figure 3. The steps in Quantitative Microbial Risk Assessment (Medema & Smeets, 2004)**

A general framework for assessing microbial risk for drinking water is proposed in "Plan for QMRA for CTSs" a work within the Microrisk project. Its main components are: Source water, treatment, distribution and exposure (Petterson *et al.*, 2004). Figure 4 is an overview over the performance of the QMRA.

The pathogen concentration in the source water reaching the off-take to the treatment plant is represented by $\mu_{off\text{-}take}$. This concentration will be dependent on the condition of the catchment area as well as on specific events such as heavy rainfalls etc and, hence, will vary between different systems. (Petterson *et al.*, 2004)

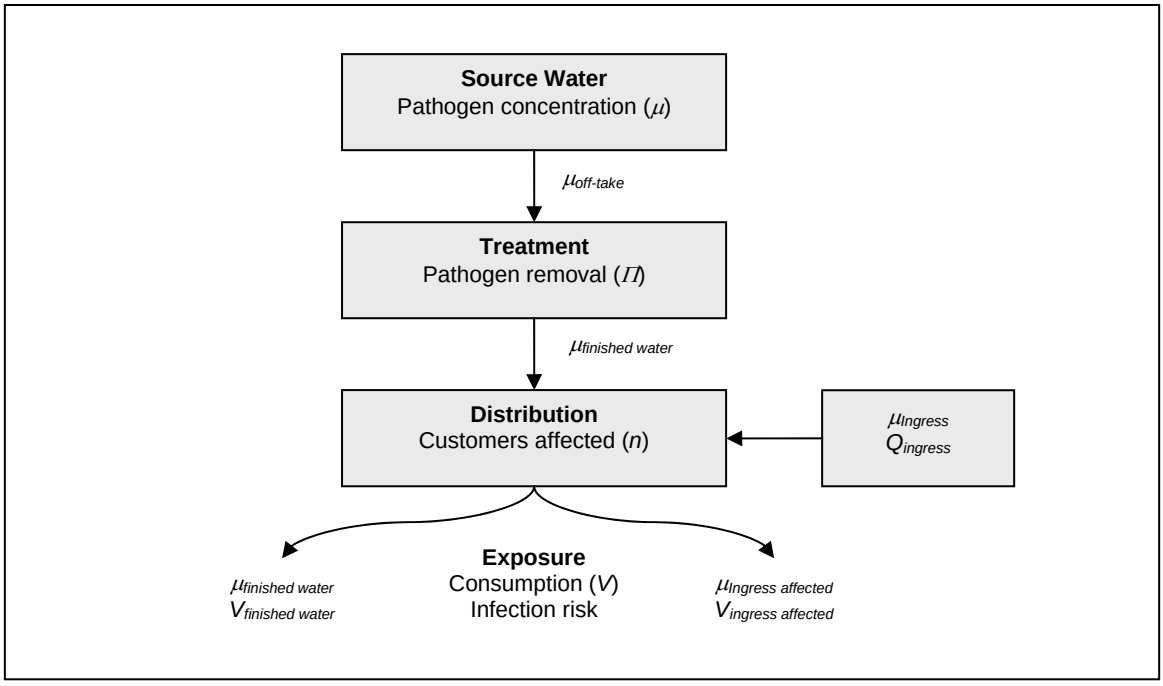

*Figure 4. General QMRA framework (Petterson et al., 2004)**

The assessment of elimination or inactivation of pathogens by treatment is a crucial factor. It is represented by *Π*. It is important to use the best available data to come up with a quantitative estimate of the pathogen concentration removal. Removal data can be developed from three sources (Petterson *et al.*, 2004):

1. Pathogen data - Measures of pathogen concentrations in inlet and outlet water is the most representative estimate of pathogen removal
2. Surrogate data - Measure of pathogen surrogate concentrations (such as particles or indicator microorganisms) in inlet and outlet water can contribute to a useful estimate of pathogen removal
3. Process performance data - Data such as SCADA data which can be used to assess reliability and assess process performance and hence reveal hazardous events

The pathogen concentration in the water leaving the treatment plant for distribution is represented by $\mu_{\text{finished water}}$. The distribution may function as a potential entrance for pathogens due to contamination through leaking pipes etc. The entering pathogen concentration is represented by $\mu_{ingress}$ and the flow with which enters $Q_{ingress}$. However, the majority of the water reaching the consumers is expected to have the same pathogen concentration ($\mu_{finished\ water}$) as the water leaving the treatment plant. The number of customers affected, either by ingress or by the finished water is represented by *n*. By assessing the average water consumption per customer, represented by *V*, and combining the results with dose-response relationships pathogen exposure can be related to health outcomes such as infection risk. (Petterson *et al.*, 2004)

2.6 QMRA and HACCP

There are some important advantages by performing the risk assessment as a QMRA and then use the values within the management system (HACCP), according to Microrisk project and the literature. First of all, the judgment about the hazards will be based on scientific quantitative calculations instead of expert opinions or historical data. Secondly, the outcome

from the QMRA is based on health risk, which allows for an approach that can minimise the overall risk in the system. (Microrisk, 2006; Havelaar, 1994)

Two important questions to be asked within the WTP:

1. Are we meeting our performances targets?
2. Is the supply system acceptably safe under normal and hazardous event conditions or do we need more risk management?

QMRA should be able to answer these questions in a scientific way with less need for "expert opinion". (Microrisk, 2006)

2.7 On-line Monitoring SCADA

For monitoring and day to day control, supervising systems are often used. Because many companies have used such systems for a long time there have been thoughts concerning the use of saved data for attentive real events.

2.7.1 SCADA data

Supervisory Control and Data Acquisition (SCADA) systems provide online monitoring of water treatment and supplies. These systems that can be used both to acquire data from and control the water supply process. And they provide around-the-clock surveillance.

SCADA systems collecting measurements, transfer the data back to central control rooms, carrying out various statistical analyses, and finally displaying the information to the operator. (Bailey & Wright, 2003)

SCADA systems enable monitoring of a wide range of parameters such as turbidity, particle size, particle count, temperature, flow, pH, conductivity, redox, ozone and oxygen. Data can also be stored and analysed as time series, and be used subsequently to provide data about duration and frequencies of possible hazardous events. Therefore SCADA data is not just applicable for day to day control but also, in practice, suitable for providing input to quantitative risk assessment such as duration of failure. (Nilsson, 2006)

However, methods for the analysis of historical data are only now being developed. More on this can be read in the associated project "The Use of Water Treatment SCADA Data to Quantify Hazardous Microbiological Events and Risks Arising - A Case Study from Sweden" (Nilsson, 2006).

2.7.2 Event identification

In the associated project (Nilsson, 2006) one of the aims was to identify microbial hazardous events with help from SCADA data. Evaluation of a big series of SCADA-data was made in order to see if hazardous events could be identified from the different parameters measured on line. This evaluation was performed with data from one year at LWTP. Some events are summarized here:

- Event Class 1, Potential process failure. A pH failure was identified for 1.5-2.2 hours. This failure can affect the capacity of inactivation of pathogens.

- Event Class 2, Breakthrough in the filtration step. 10 breakthrough events were identified with a total duration of 0.325 days.

- Event Class 3, Disinfection failure. Disinfection failure was identified for a period of 0.033 days.

2.8 Glossary

For definitions about used concepts within the HACCP-principles, see Table 2.

Table 2. Definitions found and used for different concepts and words within the HACCP-principles.

Expression	Definition
Control Point (CP)	*"Any step at which biological, chemical, or physical factors can be controlled."* (NACMCF, 1997)
Critical Control Point (CCP)	*"A step at which control can be applied and is essential to prevent or eliminate a food safety hazard or reduce it to an acceptable level."* (NACMCF, 1997; Codex 1996)
Critical Limit (CL)	*"A maximum and/or minimum value to which a biological, chemical or physical parameter must be controlled at a CCP to prevent, eliminate or reduce to an acceptable level the occurrence of a food safety hazard."* (NACMCF, 1997; USFDA, 2005) *"A criterion which separates acceptability from unacceptability."* (Codex, 1996)
Decision Tree	*"A sequence of questions to assist in determining wether a control point is a CCP."* (NACMCF, 1997)
Hazard	*"Hazards are biological, chemical, physical or radiological agents that have the potential to cause harm and/or can give rise to water quality, which is unacceptable for consumers."* (Nadebaum *et al.,* 2004) *"A biological, chemical or physical agent in, or conditions of, food with the potential to cause an adverse health effect."* (Codex, 1996) *"A biological, chemical, or physical agent that is reasonably likely to cause illness or injury in the absence of its control."* (NACMCF, 1997)
Hazardous events	*"Hazardous events are those incidents or situations that can contribute to the presence of a hazard."* (Nadebaum *et al.,* 2004)

3 Water Treatment, Microbial Removal and QMRA-components

"Knowing your system" is a prerequisite for undertaking QMRA. This chapter gives a short introduction of the main stages of a water supply system which are modelled using QMRA; they are source water, treatment, distribution and exposure. There is one section written about data collection and another about microbial inactivation. Disinfection has been given its own section because calculations for removal of pathogens through disinfection are considered more complex than the other removal processes. As a start the concept of log reduction and multiple barriers are introduced.

3.1 Log Reduction (Decimal Reduction)

The removal and inactivation of organisms in the water treatment plant is often expressed as $\log_{10}$ reduction. The reduction is a physical removal of organisms or inactivation thereof through a specific process, e.g., through disinfection. One $\log_{10}$ reduction is defined as 90 % of the organism reduced or removed, two $\log_{10}$ reductions means a 99 % reduction, 3-$\log_{10}$ reduction equals 99.9% removal and 4-$\log_{10}$ reduction will remove 99.99% of the microorganisms. (EPA, 2003 a.)

Log_{10} reduction is explained in Table 3. In this project the word Log is used and refers to Log_{10} if nothing else is pronounced.

Table 3. Explanation of log reduction

Reduction	% Reduction
1-Log	90
2-Log	99
3-Log	99.9
4-Log	99.99

Log reduction can be expressed as Decimal Elimination Capacity (DEC) (Hijnen *et al.,* 2005). LeChevallier & Au (2004) have suggested that under optimal conditions, a combination of coagulation, sedimentation and filtration should provide a 4 $\log_{10}$ reduction or more for protozoan pathogens with chlorine resistant cysts.

3.2 The Multiple Barrier Concept

Each treatment step within the WTP is a barrier working to achieve high quality drinking water. Water treatment is based upon the multiple barrier concept. The idea is that several barriers will result in a better and continuous protection. This approach allows both temporary failures in parts of the process as well as temporary deterioration in the water quality. Except for a physical obstacle a barrier can also be a management issue, such as education. (Hunter *et al.,* 2003)

One way to classify the barriers is as follows (Hunter *et al.,* 2003):

- Source water protection
- Water treatment processes
- Disinfection and distribution
- Education

The last physical barrier for inactivation of pathogens is disinfection. It has been proven that educated staff is an effective barrier. Without educated staff and well performed management

the process is not working optimal and first barriers will not be working properly. (Hunter *et al.*, 2003)

3.3 Source Water

The microorganisms in drinking water are a highly diverse group that can be divided in four groups: bacteria, viruses, protozoa, and algae. The most common and widespread health risk associated with drinking water is infectious disease caused by pathogenic bacteria, viruses, and protozoa. Consumption of drinking water contaminated with human or animal excreta is the most significant route of exposure. (Westrell, 2004)

This section will briefly describe the four microorganism groups. For further description about the index pathogens used in this project, see Appendix A. Algae are not proposed to be taking into account when QMRA is performed (Roser, 2005).

3.3.1 Microorganisms

Bacteria are single-celled microorganisms. They lack well defined nuclear membranes and other specialized parts of the cell. Bacteria vary in form but have a typical length of 1 to 15 micrometers. For most bacteria the infectious dose is high but there are exceptions such as for *Campylobacter*. (USEPA, 1999; Westrell, 2004)

Viruses are parasitic and infectious microbes composed of proteins and nucleic acids. Viruses need to be within a living cell to reproduce. The typical sizes of virus are 0.004 to 0.1 micrometers in diameter. Normally only a few viruses are needed to causes an infection since they generally are very infectious. Enteric virus is the name of virus excreted in faeces. (USEPA, 1999; Westrell, 2004)

Protozoa are microorganisms that can exist as single cells or in colonies. Some of the strains are able to produce cysts (also known as oocysts). Cysts are small reproductive bodies that are capable of protecting the organism under unfavourable conditions. The typical size of protozoa is 2 to 25 micrometer. (USEPA, 1999; Westrell, 2004)

Algae are another group of organisms that generally not directly threatens the public health, except for the toxic ones. The algae can be single or multi cellular and have typical sizes of 5 to 100 micrometer. The biggest concern about algae is their ability to create large amounts of organic matter which may have an impact on turbidity, taste and colour and hence affect the treatment efficiency. (USEPA, 1999)

3.4 Treatment

The performance of water treatment varies greatly and depends on things such as source water quality, desired end product, local conditions and much more. However, in general a conventional surface water treatment plant (WTP) often includes: Screening, Coagulation-Flocculation and Sedimentation, Filtration and Disinfection.

3.4.1 Screening

Screening is the pretreatment of the water and refers to removal of microorganisms before entering the water treatment plant. This pretreatment can for example be performed by bank infiltration, rough filters, bars and off-stream storage. This stage can, if performed well, have

a very good effect on microorganism removal and can therefore also have a great influence on the end product. (LeChevallier & Au, 2004)

3.4.2 Coagulation-flocculation and sedimentation

Coagulation is the step where small particles should form bigger particles that later can be removed by sedimentation and/or filtration. Metallic salts such as iron (III) or aluminium are often used as coagulant. Flocculation is the physical process, such as mixing, that produces a good environment for the smaller particles to aggregate to bigger particles (flocks). (LeChevallier & Au, 2004)

The coagulated/formed particles will be separated from the fluid (water) by gravity in the sedimentation step. Particles sediment to the bottom of the water column and the sludge that forms can be removed. The efficiency of sedimentation is dependent on prevailing hydraulics and flow. For an optimal operation short circuiting and turbulence should be avoided. Other parameters that affect the performance are inlet distribution and design of sedimentation basins (Pontius, 1990). Poor process control from the workers at the plant and bad sludge removal from the bottom of the sedimentation basin have a negative impact on the final result. (LeChevallier & Au, 2004)

The whole performance of coagulation, flocculation and sedimentation is depending on factors such as particle suspension, chemical dosing, mixing, pH, temperature, ionic strength and reaction time. (Pontius, 1990)

3.4.3 Filtration

Filtration removes pathogens through a combination of physical and chemical properties. The filtration can be a highly effective barrier for microbial pathogens under optimal conditions. However, if the clarification is not working properly the filtration can be almost useless. The granular high rate filtration is the most widely used filtration process but there are a wide range of different filtration designs such as slow sand filtration, nanofiltration, reverse osmosis, micro filtration, and ultra filtration. (LeChevallier & Au, 2004)

The filter in the filtration bed must periodically be backwashed since particles accumulate in it. Filtration is a good example of a process step where removal efficiency varies in time and is dependent on management. (LeChevallier & Au, 2004)

3.4.4 Disinfection

There exist different disinfectants that can be used and they have varying effectiveness for removal. Chlorine is commonly used as a disinfectant and is highly effective in removal of bacteria and viruses. Parasites such as *Cryptosporidium* are however highly chlorine resistant. Chlorine is sometimes also added to restrain microbial growth within the water treatment plant in filters, basins and channels. (LeChevallier & Au, 2004)

Another disinfectant is chlorine dioxide which has shown to be potent for microorganism removal including *Cryptosporidium* (Thurston-Enriquez *et al*., 2004). Chlorine dioxide is roughly comparable to free chlorine for inactivation of bacteria and viruses at neutral pH but at pH higher than 8.5 chlorine dioxide can be more effective than chlorine (LeChevallier & Au, 2004).

The effectiveness of disinfection with chlorine or chlorine dioxide is depending on the time that the organisms are in contact with the disinfectant and the concentration of the disinfectant residual. The Ct-value is the contact time multiplied with concentration. Other factors that have impact on the performance are temperature, pH and initial water quality. Chlorine and chlorine dioxide are very potent disinfectants but there are problems associated with the two. High concentrations of chlorine and its by-products have been found to cause harmful effects to animals. Chlorine residuals greater than 0.4-0.5 mg/l can cause problem with taste and odour. Applying a greater dose than required is also associated with unnecessary high costs. (Pontius, 1990)

Another chemical inactivation agent is ozone. The inactivation mechanism is not well understood but has been shown to work for most of the known pathogens. It is however significantly less efficient in inactivating pathogens comparing to chlorine and chlorine dioxide other than *Cryptosporidium*. A big advantage of using ozone is that it can be manufactured on site and another is the fact that ozone natural decomposition to oxygen. So it can, from an ecological point of view, be a good solution for pathogen inactivation. (LeChevallier & Au, 2004; Vinnerås & Jönsson, 2003)

UV-disinfection has been used in Europe for several decades. In the earliest state (beginning of 1990) UV was not broadly used because chlorination was considered cheaper and more reliable. When information about hazardous by-products from chlorination became available more attention was given to UV. The biggest "breakthrough" for UV-disinfection was after the discovery of its efficiency against *Cryptosporidium*. (Hijnen *et al.,* 2005)

3.4.5 Relationships between treatment processes

The multiple barrier concept is based on the idea that if one barrier works sub-optimally another barrier can compensate for it. However, within the water treatment supply several barriers may also depend on each other. Poor performance in one treatment step can affect the efficiency in the next step. For example, a pre-oxidation step can result in an improvement of the efficiency of the removal both in the sedimentation step and at the filtration (LeChevallier & Au, 2004). This is important to consider in calculations of removal efficiency in each treatment step. Secondly, this fact is underpinning the idea of minimizing the overall risk within WTP.

3.5 Distribution and Exposure

The distribution system can result both in an inactivation and as additional contaminator of pathogens. In this project the assumption was made that the distribution system will not affect the pathogen concentration. Therefore the distribution system is not discussed further. By assessing the average water consumption per customer and combining the results with the dose-response relationship, pathogen exposure can be related to health outcomes. The relationship is of importance when performing a QMRA. Consumption and Dose-response relationship will be discussed in this section.

3.5.1 Consumption

Estimates of drinking water consumption are necessary for the QMRA. Large differences in consumption habits between countries but also within the population in the same country have been reported. In "Drinking water consumption patterns in Sweden" an evaluation of Swedish drinking water consumption is performed. A study was made with a group representing the Swedish population; men and women in different age groups. The average

consumption of could tap water varied from one to twelve glasses per day with an average of 0.86 liter per day. (Westrell *et al*., 2006)

3.5.2 Dose-response

To calculate the infection risk there are relationships between dose and response that normally are used.

These relationships can be expressed as a mathematical model. The two primary models that are used for non threshold relationship within the microbial risk assessment are the exponential and Beta-Poisson dose-response models (Haas *et al.,* 1999). For available dose-response relationships see Table 4.

Exponential dose-response model (Haas *et al.,* 1999):

$$P_{\text{inf}} = 1 - e^{-r \cdot D} \qquad (1)$$

where
P_{inf} = probability of being infected
r = probability of one organism initiating an infection (The sensitivity of being affected is assumed to be constant).
D = exposure dose

Beta-Poisson dose-response model (Haas *et al.,*1999):

$$P_{\text{inf}} = 1 - \left(1 + \left(\frac{D}{\beta}\right)\right)^{-\alpha} \qquad (2)$$

where
P_{inf} = probability of being infected
α and β = dose-response parameters which are specific for each organism.
D = exposure dose

Table 4. Summary of available dose-response parameters from the three different reference organisms. The table is based on work by Westrell (2004) and Petterson et al (2004).

Reference Pathogen	Study Organism	Model	Parameters		[e]Original Data Source	[d]Data Source
Cryptosporidium	*Cryptosporidium* parvum. H.f.t.[a]	Exponential (Eq. 1)	k[c] = 238.6 r = 1/k		DuPont *et al.*, 1995	Teunis *et al.*, 1996
Cryptosporidium	*Cryptosporidium* parvum	Beta-Poisson (Eq. 2)	α=0.115	β=0.176	-	Teunis *et al.*, 2002
Norovirus	Rotavirus. H.f.t[a]	Beta-Poisson (Eq. 2)	α=0.253	β=0.422	Ward *et al.*,1986	Teunis *et al.*,1996
Norovirus	Echovirus. H.f.t[a]	Beta-Poisson (Eq. 2)	α=0.401	β=227.2	Schiff *et al.*, 1984	Teunis *et al.*, 1996
Campylobacter	*Campylobacter* jejuni. H.f.t[a]	Beta-Poisson (Eq. 2)	α=0.145	β =7.59	Black *et al.*, 1988	Medema *et al.*, 1996
Campylobacter	*Campylobacter* jejuni. Outbreak data[b]	Beta-Poisson (Eq. 2)	α=0.024	β=0.011	Van den Brandhof *et al.*, 2003 Evans *et al.*, 1996	Teunis *et al.*, 2005

Note: [a]H.f.t.= Human feeding trials. [b]Outbreak data was combined with previous human feeding studies to find overall dose-response parameter estimation. [c]r = 1/k. r = the probability of one organism initiating an infection. [d]Data Source is where data is taken from. [e]Original Data Source are articles that the articles in Data Source are referring to. The original Data Sources are not further studied.

3.6 Selecting Inactivation Data

When undertaking a QMRA the concentrations of pathogens in source water, removal capacity of each process, consumption rates and dose-response relationships need to be known. There are different ways to collect and select data. This section describes where removal data can be found.

The most reliable calculations can be made if plant specific data are used. Full-scale plant specific experiments for removal determination are both costly and time consuming. Another issue is the question on what kind of pathogens should be used; the real organism or indicators. Parameters that make it hard to estimate pathogen removal within the plant are amount and size of pathogens in the system, which due to number and scale makes it very hard to find and measure. Also the equipment for measuring a specific pathogen can be very expensive or even none existing.

An alternative to full-scale experiments is pilot scale studies or in vitro experiment/laboratory experiments. Such studies can be useful, but can also introduce uncertainty to the analysis results. Issues to consider and take into account are how a value from a laboratory experiment can be interpreted and used, what differences are there comparing to a full-scale experiment and to the reality.

The joint research program of Dutch Drinking Water Companies has issued a project with the task to create a database containing removal and inactivation data. At the moment the result is

found in a document “Elimination of microorganisms by drinking water treatment processes” that summaries the effectiveness of conventional treatment, filtration and UV-disinfection. All data collected are gathered in a database. Data on ozone, chlorine or chlorine dioxide activation have yet to be included though. The database consists of a big amount of Decimal Elimination Capacity (DEC) values which are collected from different studies during the past decades. The studies range from smaller laboratory studies to full scale experiment. Some studies are based on surrogates and others have studied actual pathogens. In “Elimination of microorganisms by drinking water treatment processes” the concept of a Microorganism Elimination Credit (MEC) can also be found. This is a value calculated by weighing the two different criteria; the scale of the study and the model organism that were used. (Hijnen *et al.,* 2005)

If data is taken from a database like this, it is important to choose data from experiment that have the same or similar conditions as the case plant. There are a lot of parameters that affect the efficiency of the removal at each step.

3.7 Microbial inactivation data

There exist a variety of data for removal and inactivation in the different processes and for different microbes. Some studies and results are presented in this section to illustrate parameters that affect the efficiency of removal. This highlights the issue on how hard it is to choose data from a database. More about variation of inactivation data is also found in Appendix B. Disinfection removal only describes removal data with chlorine and chlorine dioxide as they are the sole chemicals used for disinfection at LWTP.

3.7.1 Coagulation - Flocculation and Sedimentation

Theoretically, the range of removal processes and rate of removal through coagulation and flocculation are relative high for elimination of viruses, bacteria and protozoan (Hijnen *et al*., 2005). There are, however, big differences and variations within the different groups of organisms. The removal of viruses can vary greatly depending on what kind of coagulant being used. Studies have also demonstrated big variations between different bacteria. And there are still problems with the data on the removal of protozoa. Two reasons for this are that the amount of protozoa (which can be *Cryptosporidium)* in the water is very low making removal measurement difficult, and that there hardly exist any good methods to detect protozoa in the water (LeChevallier & Au, 2004). However, recent studies have demonstrated that the *Cryptosporidium* removal by coagulation is highly affected by the concentration of the dose of the coagulation and flocculating chemicals. Studies have also shown that iron-based coagulation is slightly better then coagulation based on aluminium. (Hijnen *et al.*, 2005)

Several studies have emphasized that an optimal coagulation dose is the most important factor in achieving coagulation removal of *Cryptosporidium*. Without a proper coagulant the protozoa can pass the filtration process. (Haas *et al.,* 1999)

3.7.2 Filtration

Most studies show that the microbial reduction in the filtration step is less efficient at the start and at the end of a filtration cycle even though this is not observed in all studies. However, some studies show that there is increased removal efficiency with the time.

The granular filtration has its best removal on particle sizes in the range 10^{-6} to 10^{-3} m. That is often the size of algae and protozoan cysts, but even some bacteria fit within this range. (LeChevallier & Au, 2004)

3.7.3 Disinfection with chlorine and chlorine dioxide

In general bacteria are effectively removed by chlorine and viruses are normally also efficiently inactivated with chlorine. Viruses generally are more resistant to chlorine than bacteria. Similarly enteric viruses can generally be more resistant to free chlorine than enteric bacteria. Protozoa such as *Cryptosporidium* are highly resistant to disinfection with chlorine (LeChevallier & Au, 2004). When using chlorine as a disinfectant for *Cryptosporidium* the Ct value has to be high in order to reach a normal, useful, log reduction. New studies have shown that the Ct value in *Cryptosporidium* disinfection is much lower for chlorine dioxide that therefore works more efficiently than chlorine. (Chauret *et al.,* 2001)

When using chlorine dioxide as a disinfectant there are significant differences in inactivation of viruses at different temperature, pH, water type and state. The inactivation rate is higher at low pH than at high (comparing pH 6 and pH 8), higher at higher temperature (comparing 5 and 15 °C) and higher for disperse than aggregated viruses. Aggregation and association with organic matter may serve to shield the virus from disinfection exposure. Therefore the aggregated viruses probably (or at least may) have a better ability to survive the disinfection than dispersed virus. (Thurston-Enriques *et al.,* 2003)

3.8 Calculating Disinfection

The case study performed in this project was based on disinfection using chlorine dioxide. Different methods can be used for calculation of disinfection removal. There are a lot of different inactivation equations to be found in the literature and these equations are often obtained by fitting data from experiments and then propose a Ct value that should be entered into the equation. EPA (2003 a.) has proposed the use of a baffling factor (BF) which takes into account the variation of flow time depending on the design of contact tanks that are being used. Another method is basing the calculations on the principles of Continuous Stirred Tank Reactor (CSTR). Both methods try to simulate the reality as close as possible. By fitting result from removal experiment to full-scale conditions methods like these are developed. (Smeets *et al.,* 2005)

3.8.1 Disinfection removal

One way of calculating inactivation is by a first order kinetic reaction equation (Oppenheimer *et al.,* 1999):

$$\frac{N_t}{N_0} = e^{-k \cdot Ct} \qquad (3)$$

where
N_t and N_0 = number or concentration of organisms at time t and time zero respectively.
k = inactivation rate constant which is different for each microorganism.
Ct = contact time · concentration

This equation is valid for ideal batch or plug flow reactors.

3.8.2 US-EPA Guidelines Manual - Baffling factors

When calculating disinfection EPA (2003 a.) has proposed that the Ct value should be calculated with help from a baffling factor (BF), see Table 5. This factor will take into account that the water flow varies, depending on where it flows. The flow is different in a basin, pipe or reservoir. The time that a particle is within the system will vary a lot, depending on how the water flows. (EPA, 2003 a.)

Calculated Ct = (Ct_{calc}),

$$Ct_{calc} = C \cdot T \qquad (4)$$

where
T = contact time for the disinfectant [min]
C = residual disinfectant concentration [mg/l]

The theoretical detention time (TDT) should be multiplied by the baffling factor to give the corrected contact time T (EPA, 2003 a.). Synonymous to theoretical detention time (TDT) is the expression hydraulic residence time (HRT).

$$TDT = \frac{V}{Q} \qquad (5)$$

where
TDT = theoretical detention time
V = volume
Q = flow

$$T = TDT \cdot BF \qquad (6)$$

Table 5. Proposed Baffling Classifications. From EPA Guidance Manual (2003 a.).

Baffling condition	BF	Baffling Description
Unbaffled	0.1	None, mixing basin, low length to width ratio, high inlet and outlet flow velocities
Poor	0.3	Single or multiple unbaffled inlets and outlets, no intra-basin baffles
Average	0.5	Baffled inlet or outlet with some intra-basin baffles
Superior	0.7	Perforated inlet baffle, serpentine or perforated intra-basin baffles, outlet weir or perforated launders
Perfect (Plug flow)	1.0	Very high length to width ratio (pipline flow), perforated inlet, outlet, and intrabasin baffles

3.8.3 Continuous Stirred Tank Reactor (CSTR)

Continuous Stirred Tank Reactor (CSTR) is based on the concept of plug-flow. The method assumes the contactor consists of a series of CSTRs. General CSTR equation (EPA, 2003 b.):

$$\frac{N_i}{N_{i-1}} = \frac{1}{\left(1 + \frac{k \cdot c \cdot t}{m}\right)^m} \qquad (7)$$

where
N_i = concentration in tank number i.
m = number of tanks
Ct = contact time · concentration
k = inactivation rate constant which is different for each microorganism.

$$k = A \cdot e^{-E/(R \cdot T)} \qquad (8)$$

A = frequency factor [L / (mg · min)]
E = activation energy [J / mol]
R = 8.314 [J / (mol · K)]
T = temperature [K]

4 Choice of QMRA Simulations in the Light of HACCP

This chapter provides the reader with what issues to simulate in a QMRA in order for the results to be valid to use in HACCP. In the three first sections a number of issues that could contribute to the three first HACCP-principles are suggested along with some background for the choices made. The choice of interesting issues to simulate is opted by the author after discussion with associates within work package 6 in Microrisk and in the light of HACCP. The fourth and last section summarizes the choices.

4.1 HACCP Principle 1

In Principle 1 one aim is to make judgment about which pathogens that must be involved in HACCP.

There already exist statements of the most important hazards for water supply systems. For example Havelaar (1994) writes that for drinking water supply, the main microbial hazards are:

- Pollution of raw water sources from viruses, bacteria and protozoan (oo) cysts.
- Growth of pathogenic bacteria or free-living amoebae in raw or treated water.

WHO (2004) has established that the most common and widespread health risk associated with drinking-water is infectious diseases caused by pathogenic bacteria, viruses, and protozoa.

Hence there are strong reasons for focusing on pathogens and documents such as "A Guide to Hazard Identification & Risk Assessment for Water Supplies" (Nadebaum *et al*., 2004) can be a good start for identification of hazards.

Infection risk under normal condition and additional infection risk from different events are simulated. The result from the QMRA is then presented as how many infection one particular hazard (pathogen) can cause. Results about infection risks could be a basis for selection of hazards for the HACCP.

4.2 HACCP Principle 2

The question about how to choose CCP is not easily answered. Here it was suggested that a starting point when looking at CCP is to use each treatment step within the treatment plant. This was also suggested by Havelaar (1994) in the article "HACCP and the drinking water supply".

To make judgement about the importance of each treatment step for each pathogen that is simulated a factor sensitivity analysis is performed.

4.3 HACCP Principle 3

In order to establish critical limits based on health targets an acceptable risk of infection must be defined. There is yet no generally agreed acceptable risk value in Sweden for water infections. The Dutch Drinking Water Degree required level of safety allowing only one infection per 10 000 persons and year has been used as reference value in this project.

One set of simulations is made under normal conditions to see what the incoming concentrations are allowed to be, so that only one infection per 10 000 persons and year will occur for each pathogen. Another set of simulations is made to find which concentration that is allowed to come in to the plant if one process is working poorly. This is used for making judgement about what incoming concentration the plant can accept as a critical limit.

Another thought that have been growing during the progress of this project is if duration of failure can be used in a good way for decision making. By simulating a relevant process failure (e.g., loss of chlorine leading to poor disinfection) during different periods of time it is possible to obtain the increase in infection risk as a function of time. Plotting infection risk against duration of failure could give the decision-maker a good overview about the infection risk when a removal process is working poorly. This duration-infection figure then tells the operator for how long time a process failure is okay before the infection risk becomes too high.

Simulations are also made to calculate increased infection risk for different occurring hazardous events. The results are used to estimate how many of these hazardous events that are allowed to happen before the acceptable infection risk is exceeded.

4.4 Summary of what to Simulate in QMRA

Summarising the previous sections in this chapter the main issues to be considered are:

- Infection risk under normal conditions - base line scenario
- Critical incoming concentration under base line conditions
- Additional infection risk for hazardous events
- Infection risk versus duration of failure
- Sensitivity analysis

More details about these issues can be found in section 6.2.

Part 2 - Case Study

5 System Description

This chapter describes the water supply system in Gothenburg in general and the Lackarebäck Water Treatment Plant in detail. A system description is one important preparation step before undertaking a HACCP. This chapter gives background data for the two associated projects and is therefore almost identical in the two reports.

*5.1 Water Treatment in Gothenburg**

Gothenburg Water and Wastewater Works supplies drinking water in the Gothenburg area. The river of Göta älv is used as source water and the drinking water is produced at Alelyckan Water Treatment Plant (AWTP) and Lackarebäck Water Treatment Plant (LWTP) on the outskirts of Gothenburg.

5.1.1 Source water

Gothenburg is supplied with water from the largest river in Sweden, Göta älv. The river is a recipient for communities, industries and agriculture, and acts as a raw water supply for about 700 000 people. The catchment area is 50 180 km^2, corresponding to about 10 % of the surface area of Sweden. (Stenström & Åström, 2005; Vattenvårdsförbundet, 1996)
The upstream catchment is sparsely populated. An approximate flow of two cubic meters of water per second is drawn from the river. This equals less than 0.5 % of the total flow. (Va-verket Göteborg, 2005)

At normal conditions, the raw water quality of Göta älv is very good. However, temporary deviations occur due to for example heavy rainfall or snow melting, followed by surface run off or from disturbances in upstream wastewater treatment plants. Hence, the water quality in Göta älv is measured regularly. Together with upstream incident reports this information is used to forecast microbial events in the raw water. Based upon these events the intake at Lärjeholm is routinely closed for periods up to one month. Overall, the intake is closed for approximately one third of the year. (Va-verket Göteborg, 2005; Bergstedt, 2005)

5.1.2 Gothenburg water supply system

A total volume of 170 000 cubic meter of drinking water is produced each day at AWTP and LWTP. Each plant produces about 50 % of the total volume. AWTP acquires its raw water directly from Lärjeholm. The raw water for LWTP is directed from Lärjeholm to lake Lilla Delsjön and lake Stora Delsjön (see Figure 5). The lakes serve as reservoirs with a residence time of approximately four months. (Stenström & Åström, 2005)

However, the residence time does not always equal the time it takes for water pumped to lake Lilla Delsjön to reach the intake at Lackarebäck. This time can, under unfavourable conditions, be approximately a couple of weeks depending on wind and lake turn-over. Lake Rådasjön is a nearby-located lake, which is used to maintain the level in lake Lilla Delsjön and lake Stora Delsjön. Lake Rådasjön can also act as the raw water source if the water in lake Lilla Delsjön and lake Stora Delsjön is insufficient. (Bergstedt, 2005)

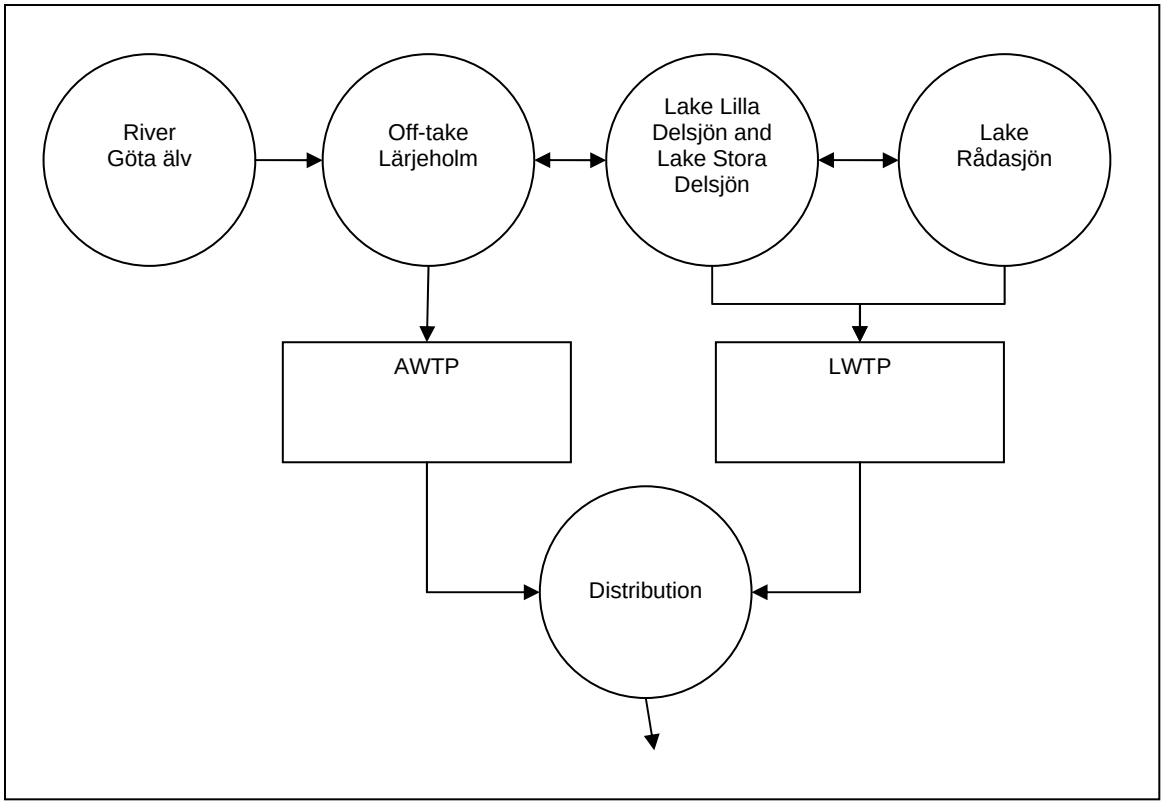

Figure 5. Schematic figure of Gothenburg water supply system. AWTP is the abbreviation for Alelyckan Water Treatment Plant and LWTP stand for Lackarebäck Water Treatment Plant.*

5.1.3 Lackarebäck Water Treatment Plant (LWTP)

LWTP was commissioned in 1968. The treatment train is divided into a North and a South section, where the North section consists of process lines 1, 3, 5, and 7 and the South section consists of process lines 4, 6, and 8, see Figure 6.

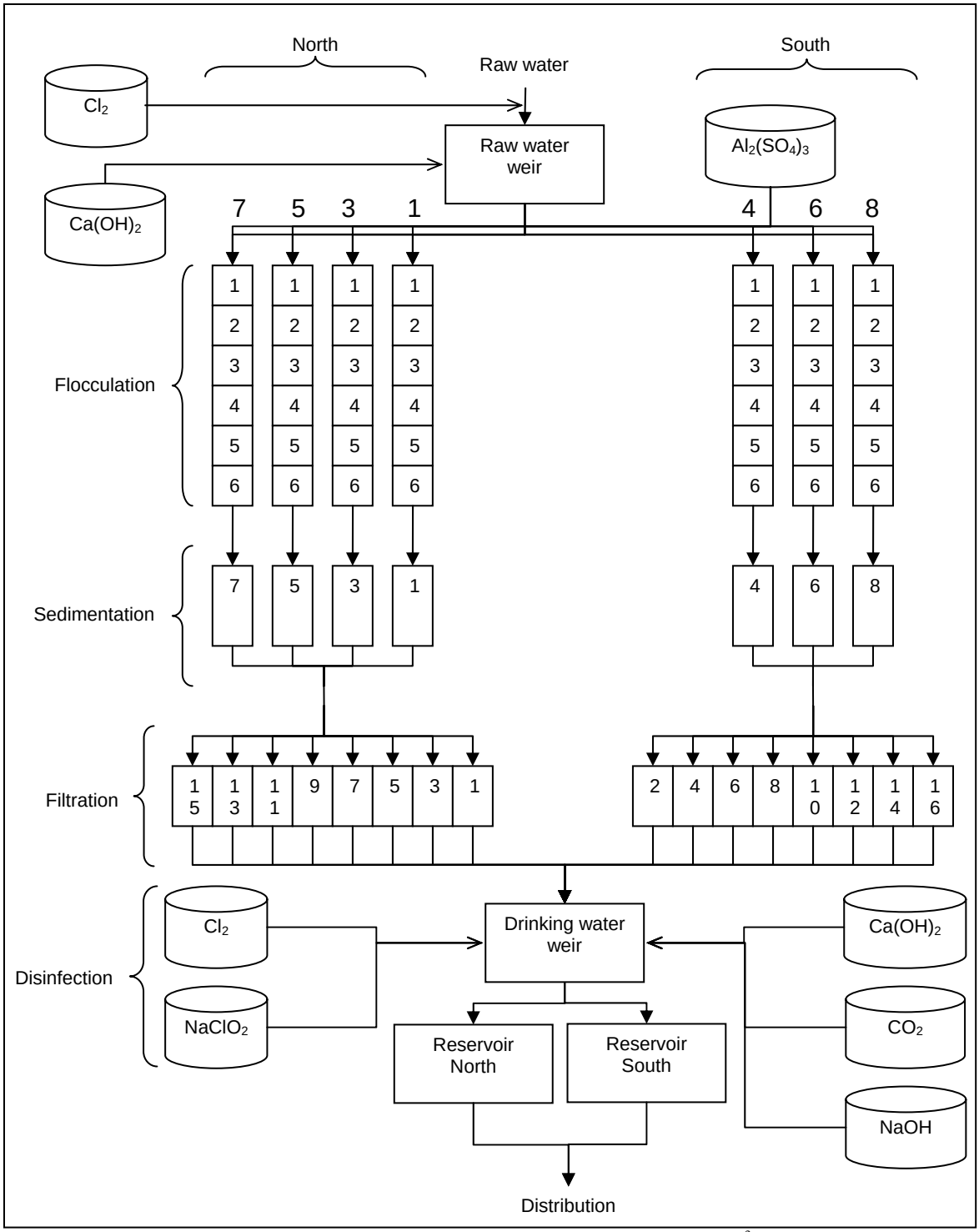

Figure 6. Process scheme of LWTP (To simplify the scheme, the Cl_2 and $Ca(OH)^2$ tanks have been depicted as two separate tanks)*

All process lines, except line 7 which also includes flotation, have similar design. The treatment process includes (VA-verket Göteborg, 1998):

1 Pre-dosing: pH adjustment and chlorination if the water temperature exceeds 12 °C
2 Flocculation with aluminium sulphate (alum)
3 Sedimentation
4 Activated carbon filtration

5 Post-dosing: pH adjustment
6 Disinfection through chlorination
(VA-verket Göteborg, 1998)

There are two possible raw water off-takes from Lake Stora Delsjön located at depths of 8 and 16 meters. Usually the off-take at 8 meters is used but under special circumstances, such as algae bloom or high water temperatures, an off-take at 16 meters is used. (Olsson, 2005)

If the temperature of the raw water exceeds 12 °C, chlorine is used in the raw water weir (Figure 7) to prevent microbial growth in the filters. Chlorine is dosed in the pipe running to the raw water weir and the dosing is proportional to the raw water flow. The aim is to achieve a chlorine residual of 0.08 - 0.10 mg/l in the clarified water. In the raw water weir, the pH is also adjusted to 9.5 - 10 with lime ($Ca(OH)_2$). This is done to promote optimal flocculation. (Olsson, 2005)

Figure 7. Upper left: raw water weir. Upper right: flocculation mixing chamber. Lower left: GAC filters. Lower right: drinking water weir.*

Flocculation is carried out in a six chamber system where alum is dosed in chamber one. The particles aggregate during slow mixing. Sedimentation occurs in Lovö basins (double bottoms). Most of the particles sediment to the bottom. Sludge scrapers remove excessive sludge from the basin beds. Sedimentation is followed by granulated activated carbon filtration (GAC). Aggregates and smaller dissolved substances causing problems with smell and taste like geosmin are absorbed by the carbon. The filter needs to be backwashed on a regular basis. Head loss is used to decide when the backwash should take place. The filters are backwashed automatically within an interval of 24 to 35 hours. If the head loss appears before 24 hours, the filter is not washed automatically. Drinking water is used for backwashing. Initially, a small flow is applied to break the bed. Subsequently the filter is

turned over with volumes approximately twice the filter volume. The aim is to get a 30 % expansion of the carbon during 15 minutes. The backwash water is discharged to a wastewater treatment plant. (Olsson, 2005)

There is no more chlorine left from the pre-chlorination after the filtration step (Bergstedt, 2005).

As disinfectant chlorine and chlorine dioxide are used, chlorine water (Cl_2) is added together with sodium chlorite ($NaClO_2$) to receive an oversaturated chlorine dioxide solution with respect to chlorine gas.

$$Cl_2 + 2NaClO_2 \Rightarrow 2ClO_2 + 2NaCl$$

1.4 g/m^3 $NaClO_2$ and 0.61 g/m^3 Cl_2 is added to form a solution of 1 mg ClO_2/l.

At the time LWTP was built the Ct-concept was not thought of as an important concept. The result from this was that the reservoirs were not built to create a long contact time. This means that resident time can not just be calculated from flow rate and volume since some water will stay longer in the reservoir and some water will pass very quick. This makes it hard to calculate the Ct-value properly. (Bergstedt, 2005)

6 Method

This chapter starts with a schematic figure over how the plant is simulated in @risk. Words and abbreviations that are used in the model are found here. The next section explains the different simulations that have been done and to a certain degree also why. The last section summarizes data that have been used in the simulations.

6.1 The Model

A simple model was created in an MS Excel program. All simulations were made in this program that was connected to Palisade @risk v.4.5 (@risk). @risk made it possible to use a distribution function instead of point values (@risk, 2004). The results were presented with 95-percentile.

A schematic figure over the model and abbreviations used in Excel is presented in Figure 8. The model was based on the general QMRA framework proposed in "Plan for QMRA for CTSs" (Petterson *et al.*, 2004).

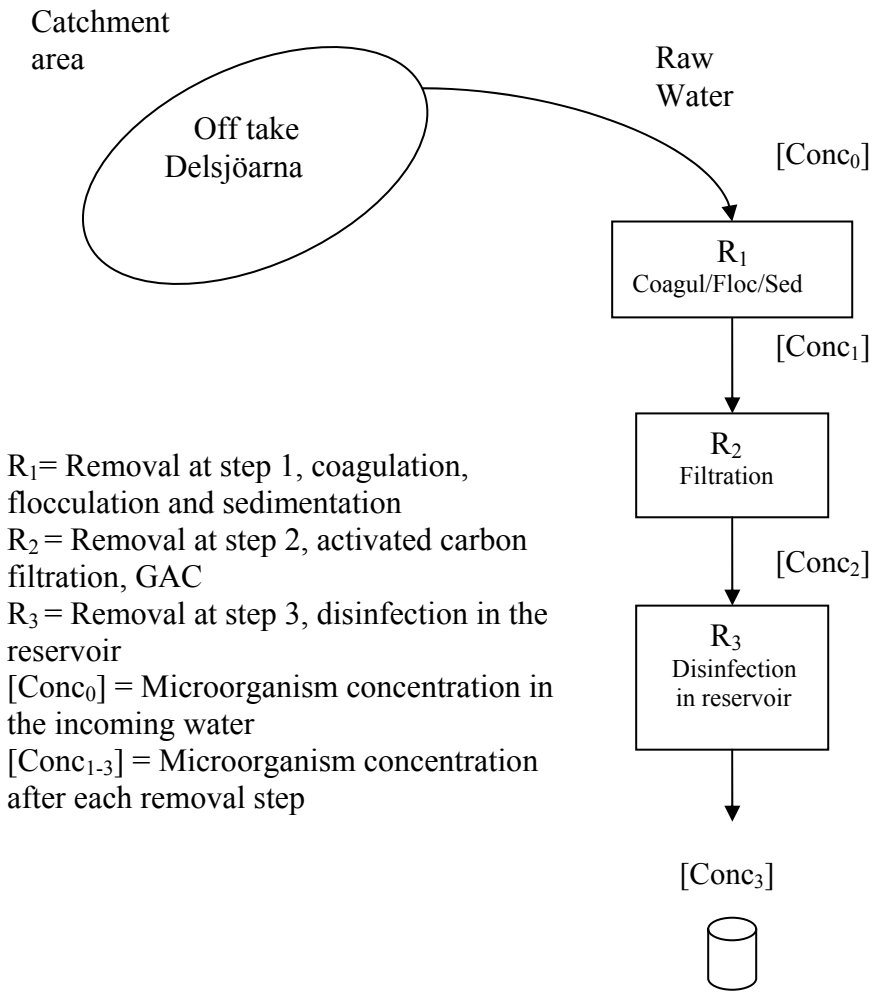

Figure 8. A schematic flow diagram showing the model and summery of abbreviations that was used.

Pathogen abbreviations within Excel were; *Cryptosporidium* (C), Norovirus (V) and *Campylobacter* (B).

The incoming microorganism concentration was labeled $Conc(X)_0$ where X is the microorganism that was modeled. After each inactivation step in the process a new pathogen concentration, $Conc(X)_{1-3}$ were acquired. This approach (i.e., dividing up all treatment steps) makes it possible to receive the concentration after each inactivation step and compare it to a tolerated concentration level established for the plant. An assumption was made that the distribution system will not affect the concentration. Therefore $Conc(X)_3$ is considered to be the concentration in the outgoing drinking water reaching the consumer.

The removal of microorganisms was divided in three different steps. The first removal step (R_1) contains coagulation, flocculation and sedimentation. The second removal step (R_2) is the filtration removal, performed with active carbon (GAC). The third step (R_3) is the disinfection with chlorine dioxide. R_{tot} is the total removal within the plant according to this model. Some parts (sheets) from the model in Excel can be found in Appendix C.

6.2 Simulations

This section is written to present the different simulations that were undertaken. To some degree it also explains the course of action made when performing them. Results from simulations in @risk are presented as infection risk (P_{inf}) and annual infection risk (annual P_{inf}). Annual P_{inf} gives the answer to how many infections per 10 000 persons and year that can be expected based on the in data to the simulations. 95th percentile was used as reference value but other percentiles are also being presented for some simulations. Indata that are used for the simulations are presented in section 6.3.

6.2.1 Base line scenario

The first task was to analyse the infection risk under "normal" conditions. The following statistics have been calculated for each organism:

- The median and average infection risk.

- The 95th, 97.5th and 99th percentile values of infection risk.

6.2.2 Critical incoming concentration

With a fixed value for log reduction (base line point value, no distribution functions) one critical incoming concentration was searched for. By seeking the incoming concentration that results in one infection per 10 000 persons and year the critical incoming concentration was established for each pathogen. This simulation answered the following question: What incoming concentration (point value) is allowed under normal operating conditions?

Conservative simulations were also made to calculate the incoming concentration allowed if all three removal steps performed poorly at the same time (It was considered that "poorly" means that all treatment barriers perform at the 5th percentile of variability). The aim with this simulation was to receive the highest concentration of pathogen per litre that can be accepted in the incoming water under these conditions. The simulation is answering the question: What incoming concentration (point value) is allowed under "poor" conditions.

Statistics that have been calculated for each organism:

- The 95th percentile.

6.2.3 Hazardous events

Additional infection risks were simulated for three different events. The events were taken from the associated project (Nilsson, 2006) obtained from SCADA data analysis. The events were all concerning failure in the treatment process. The same in data as for the base line scenario were used.

Statistics that have been calculated for each organism:

- The 95th percentile.

6.2.4 Infection risk versus duration of failure

As a start for establishing critical limits the duration of failure was calculated for *Cryptosporidium*. The issue to address was tolerated failure period. One removal process within the system was set to zero (process failure) for different time durations. For each time duration the result was presented as infections per 10 000 persons and year. The process failure was simulated between 0.001 days to 1000 days. Simulations were made with no coagulation, flocculation and sedimentation (R_1). All other parameters were the same as for the base line condition.

Statistics that have been calculated for *Cryptosporidium*:

- Average, 75th, 95th, 97.5th and 99th percentile.

The results were presented as curves; time of failure on the x-axle and infection risk on the y-axle. These curves can be used as a base when deciding what duration of failure that can be allowed depending on accepted risk.

6.2.5 Sensitivity analysis

To understand the importance of the different parameters in a model containing several steps and many uncertain parameters a sensitivity analysis may be used. The sensitivity analysis points out the most important part in the model and is a tool used for determining what data that have the most impact.

A sensitivity analysis can be performed by a calculating the factor sensitivity (FS). The factor shows the importance of one parameter compared to the other in the simulated process. (Zwietering & Gerwen, 2000)

$$FS_P = \log_{10}\left(\frac{P_x}{P_{average}}\right) \qquad (9)$$

where
P_x = infection risk when one parameter x in the model is changed (See Table 10 for used data).
$P_{average}$ = infection risk at base line conditions.

Factor sensitivity analysis were performed for each step in the QMRA: Incoming source water, the three different removal steps, consumption of water and the impact of different dose-response relationships that are used.

Simulations were also performed to investigate the variation of the DEC value when using different methods of calculating disinfection.

6.3 Data used for Simulations

This section presents the input data used for the simulations. Point estimations or distribution functions were used when simulations were performed. For explanations and equation of distribution functions in @risk, see Appendix D.

Table 6 is summarizing all input data used for the base line scenario.

All simulations concerning incoming concentrations are made by Petterson (2005) based on data samples from Göta älv and the raw water intake at Lackarebäck. *Cryptosporidium* counts were obtained from 24 samples taken at LWTP raw water intake. A Gamma distribution was fitted to the data set. For Norovirs no positive values was found in the raw water intake, therefore the 95% upper uncertainty concentration was used for the 19 samples taken at Göta älv. The reduction of Norovirus in Delsjön was based on Enterococci removal relationship found in Delsjön. The value for *Campylobacter* was also based on 19 samples taken at Göta älv. The reduction of *Campylobacter* in Delsjön was based on E.coli removal relationship found in Delsjön. (Petterson, 2005)

Data for log removal at the coagulation, sedimentation and filtration step come primarily from "Elimination of microorganisms by drinking water treatment processes" (Hijnen *et al.,* 2005) and the data-base that was created for the report. When choosing this data an evaluation of the reduction was made in the light of what was written in section 3.7 about the different inactivation and reduction between different pathogens etc. For these removal steps triangle distribution were used with a most likely, maximum and minimum value when simulations were made. For discussion about used data see Appendix E and for explanation about the triangle distribution see Appendix D.

Removal data for disinfection treatment was based on a broader literature review that resulted in a smaller data base. To be able to calculate the cumulative Ct-value for the disinfection an incremental calculator was created in Excel based on conditions at LWTP. As base the CSTR equation was used and kinetic coefficients were taken from the literature (see section 3.8). For disinfection simulations a DEC was given as 5^{th} percentile, 95^{th} percentile and most likely value. These values are results from calculations in @risk. Table 7 is summarizing statistics for disinfection.

The consumption data was taken from a Swedish cold water consumption study where consumption was presented with 10^{th}, 50^{th} and 90^{th} percentiles. The study was performed on a Swedish population comprising 157 persons. (Westrell *et al.,* 2006).

Simulations were not including pre-chlorination which is performed in the plant if the temperature in the raw water is equal or higher than 12 °C. Chlorination of the raw water weir has the main purpose of controlling and removing algae and counteracts growth in the filter (Olsson, 2005). Therefore an assumption was made that the pre-chlorination step would not have any big impact on the microorganism removal in the case study.

Existing relationship between dose and response was used for *Campylobacter* and *Cryptosporidium*. The judgment about which parameters that should be used for the base line scenario was based on expert statement within work package 6 in Microrisk. Dose-response relationship for Norovirus is still under development and therefore the relationship for Rotavirus was used. See Table 4 for more information about existing dose-response relationships.

In the CSTR equation there is a k value that varies with temperature. When performing calculations with CSTR the year was divided into different seasons. Calculations with different k values will result in different DEC values valid for different periods of the year (see Table 15). Both temperature and flow data were taken from Lackarebäck and therefore the DEC values were valid specifically for LWTP. For base line simulations the k value was based on general temperature data for one year with temperature varying between 2.8 and 19.7 °C. The other equations used in the comparison to DEC removal were taken from the disinfection data base created for this project, see Appendix F.

Table 6. Data used for base line simulations. For explanation about risk functions such as riskgamma, risktriangel, risklognormal see Appendix D.

Base line	Pathogens			Comments
	Cryptosporidium	Norovirus	*Campylobacter*	
Source water Göta älv	--	0.23[a]	0.047[b]	Organisms per l
Delsjö removal[c]	--	1.53[d]	1.87[e]	Value in DEC
Source water LWTP	Riskgamma (0.081,0.21)[f]	$0.23 \cdot 10^{-1.53}$	$0.047 \cdot 10^{-1.87}$	--
Coag/Foc/Sed[g]	Risktriang (0.5,1.54,2.7)	Risktriang (0.49,1.42,2.7)	Risktriang (0.4,1.6,2.53)	Value in DEC
Filtration[h]	Risktriang (0.7,1.24,2.1)	Risktriang (0.3,1,1.2)	Risktriang (0.5,1.07,2.9)	Value in DEC
Disinfection[i]	5^{th} perc = 0.41 mean = 0.57 95^{th} perc = 0.90	5^{th} perc = 2.21 mean = 2.43 95^{th} perc = 2.77	5^{th} perc = 3.77 mean = 3.89 95^{th} perc = 4.08	Value in DEC. See Table 7 for disinfection statistics
Consumption[j]	Risklognormalt(10%,0.4,50%,0.8,90%,1.6)			l/day
Dose-response functions	Exponential $k^k = 238.6$	Beta-Poisson $\alpha = 0.253$ $\beta = 0.422$	Beta-Poisson $\alpha = 0.024$ $\beta = 0.011$	See section 3.5.2 dose-response

Note: [a]Based on 19 samples taken at Göta älv, point value (Petterson, 2005). [b]Based on 19 samples from Göta älv, point value (Petterson, 2005). [c]When no concentration data was available for raw water intake from LWTP data was taken from Göta älv. Before the water enters LWTP it will pass Delsjöarna which will work as an extra removal step. [d]Point value for reduction of Norovirus in Delsjön (Petterson, 2005). [e]Point value for reduction of *Campylobacter* in Delsjön (Petterson, 2005). [f]Based on 24 samples taken at LWTP. Pathogen concentration was multiplied with a recovery factor of 2.5. (Petterson, 2005). [g,h]Data based on "Elimination of microorganisms by drinking water treatment processes" (Hijnen *et al*., 2005) and reasonable assumptions, for more information about removal see Appendix E. [i]Data from simulations made by the author in @risk. [j]Data from Drinking water consumptions patterns in Sweden, (Westrell *et al.*, 2006), [n = 157]. [k]k = 1/r where r is the probability of one organism initiating an infection. DEC = Decimal Elimination Capacity. CSTR = Continuous Stirred Tank Reactor.

Table 7. Statistics and coefficients for disinfection with ClO_2 using CSTR equation. See section 3.8.3 for more information about CSTR equation.

Data	*Cryptosporidium*	Norovirus	*Campylobacter*
A [1/(mg min)]	[a]$6.31 \cdot 10^8$	[b]$6.31 \cdot 10^8$	501187.2[c]
E [J/mol]	59087[a]	48350.96[b]	23756[c]
R [J/(mol·K)]	8.314	8.314	8.314
T[d] [°C]	min = 2.8 mean = 9.7 max = 19.6		
t[e] [min]	min = 218 max = 712 mean = 399		
C[f] [mg/l]	1 (ClO_2) ; half-life 14 h		
m [ea.]	1 ea. Tank		

Note: [a]EPA (2003 b.). [b]AWWA (1991). [c](Rice *et al*., 1999). [d]Temperature data from LWTP, based on one year of measuring (Bergstedt, 2005). For calculations a created lookup table was used. [e]Contact time in the reservoir based on water flow and reservoir volume (25000 m^3), LWTP (Bergstedt, 2005). [f]Starting ClO_2 concentration LWTP based on data from LWTP (Bergstedt, 2005). [e,f]Ct (contact time·concentration) was calculated using lookup table combined with starting concentration of ClO_2 and the half-life time. A = frequency factor [1/(mg min)]. E = activation energy [J/mol]. R = 8.314 [J/(mol·K)]. T = temperature in Kelvin [K].

Table 8 presents total log removal under normal conditions and total log removal if treatment barriers perform at the 5th percentile of variability for each pathogen. These values are results from simulation made for this project in @risk. Data consists of point values that were kept fix when critical incoming concentrations were estimated.

Table 8. Total log removal under normal conditions and under poorly performance at 5th percentile. The values are results from simulations in @risk, made by the author of this project.

Microorganism	Total log removal[a]	Total log removal[b] at 5th perc
Cryptosporidium	3.5	2.1
Norovirus	4.8	3.5
Campylobacter	6.9	5.3

Note: [a]Mean value of the total log removal under normal conditions at LWTP. [b]Total log removal at 5th percentile of variability, data from calculations in @risk.

For event simulations data were used based on results from the associated project, see section 2.7.2 (Nilsson, 2006). Input data for events are summarized in Table 9.

Table 9. Input data for events taken from the associated project (Nilsson, 2006). For explanation about the events see section 2.7.2 Event identification or read more in the associated project.

Event	Condition	Description	time of failure
Coagulation Flocculation Sedimentation	Potential process failure	pH disruption for 1.5-2.2 hours	[a]Uniform(1.5,2.2)/24
Filtration	Summation of breakthrough periods	10 events = 0.325 days	0 for 0.325 days
Disinfection	Disinfection failure	No treatment for duration period of 0.033 days	0 for 0.033 days

Note: [a]Uniform function is explained in Appendix D.

Factor sensitivity (FS) was calculated for six different stages. Input data for source water was based on worst case concentration sampled at LWTP (Petterson, 2005). The data was from the same measuring as for base line scenario. The lowest Decimal Elimination Capacity (DEC) value (in relation to base line data) was used as worst case for coagulation-flocculation-sedimentation (R_1). For filtration (R_2) and disinfection (R_3) worst case was considered as if the removal was zero. FS was calculated for *Cryptosporidium* if the dose-response relationship were of Beta-Poisson instead of exponential shape. The impact on the result for Norovirus and *Campylobacter* was also calculated by using different suggested α and β values. All dose-response data were taken from Table 4. A summary of input data for FS calculations is given in Table 10.

Table 10. Data used for calculating factor sensitivity for each pathogen.

Stage	*Cryptosporidium*	Norovirus	*Campylobacter*	Comments
Source water[a]	0.24[b]	36.57	0.14	Pathogen/l
Coag/Foc/Sed[c]	0.5	0.49	0.4	DEC-removal
Filtration	0	0	0	DEC-removal
Desinfection	0	0	0	DEC-removal
Vol consumption	3	3	3	l/person
Dose-response functions	Beta-Poisson $\alpha = 0.115$ $\beta = 0.176$	Beta-Poisson $\alpha = 0.401$ $\beta = 227.2$	Beta-Poisson $\alpha = 0.145$ $\beta = 7.59$	See section 3.5.2 for further explanation.

Note: [a]Incoming concentration for pathogens are based on data from LWTP and are calculated as for base line scenario (Petterson, 2005). Upper 95th percentile value is used as worst case. [b]The *Cryptosporidium* value is multiplied with a recovery factor of 2.5. [c]Coagulation, flocculation and sedimentation.

7 Results from QMRA

This part will present data from simulations made with @risk. What was supposed to be simulated and why are presented earlier in the project. If nothing else is stated data being presented are based on 95th percentile values. Tables with results from simulations are found at the end of the chapter. The simulations were performed to show how QMRA could be used in HACCP and what kind of results which could be obtained. Although the aim has been to use best available input data and relevant scenarios have been chosen quantitative results in this project should not be used, as the results are very sensitive to uncertainty in some parameters.

Under base line conditions *Cryptosporidium* and Norovirus showed an annual P_{inf} between 1 - 2 infections per 10 000 persons and year. Simulations with *Campylobacter* showed an annual P_{inf} of approximately $1 \cdot 10^{-2}$ infections per 10 000 persons and year. For *Cryptosporidium* and Norovirus the annual P_{inf} is exactly on the level of what is acceptable (as stated in this project). However, it should be remembered that a 95% upper uncertainty concentration was used for Norovirus which is a very high value and not very representative for base line conditions. Therefore the simulations for Norovirus should be considered as conservative. When using 99th percentile values the infection risk was in the range of $2 \cdot 10^{-2}$ - 6 infections per 10 000 persons and year for each pathogen (see Table 11). Simulations like this provide good feedback on how the plant is working under normal conditions.

If the inlet is open and the water is taken directly from Göta älv, i.e., not passing Delsjön, the infection risk would be more then 70 times bigger for *Cryptosporidium* and 30 times bigger for Norovirus. This emphasizes the importance of Delsjön as an inactivation step for LWTP.

Calculations of critical concentrations leading to one infection per 10 000 persons and year under base line conditions resulted in incoming concentration of 0.03, 0.005 and 0.09 organisms l^{-1} for *Cryptosporidium*, Norovirus and *Campylobacter* respectively. For the first two pathogens these concentrations are in the same order as the data used for base line simulations. For *Campylobacter* the value of 0.09 organisms l^{-1} which is almost 150 times bigger compared to incoming concentration used at base line conditions. The *Campylobacter* concentration in the incoming water can therefore be judged as very safe (under base line conditions) and an event that increases the *Campylobacter* concentration must be quite big to increase the infection risk to an unacceptable level.

Calculations of critical concentrations leading to one infection per 10 000 persons and year when treatment steps are working poorly show that the incoming concentration for each pathogen must be 7 times less than under normal conditions if the acceptable value of one infection per 10 000 person and year is not to be overstepped. Results from critical concentration simulations are found in Table 12.

Results from simulating additional infection risk for the different events showed that pH failure had the biggest impact on *Cryptosporidium* and Norovirus with an additional annual P_{inf} of $7 \cdot 10^{-3}$ and $5 \cdot 10^{-3}$ infections per 10 000 persons and year, respectively. This event did not show any additional P_{inf} for *Campylobacter*. Event two, filtration breakthrough had most impact on *Cryptosporidium* (annual P_{inf} $2 \cdot 10^{-2}$ infections per 10 000 persons and year) but did also increase the annual P_{inf} for Norovirus with $7 \cdot 10^{-3}$ infections per 10 000 persons and year. Event 3, disinfecting failure, was the only event that resulted in an additional infection for

Campylobacter ($4 \cdot 10^{-3}$ infections per 10 000 persons and year). Norovirus showed an additional infection risk of $3 \cdot 10^{-2}$ infections per 10 000 persons and year compared with the *Cryptosporidiums* value of zero. See Table 13 for additional infections for each event.

The results from simulating annual P_{inf} if the coagulation-flocculation-sedimentation removal was not working under different time-duration resulted in a duration-infection figure, see Figure 9. Simulations were only made for *Cryptosporidium* but should be performed for each removal stage and pathogen.

Factor sensitivity (FS) analysis showed that the three most important parameters for *Cryptosporidium* were source water, filtration step (R_2) and used dose-response relationship. For Norovirus and for *Campylobacter* the three most important parameters were source water, disinfection step (R_3) and the parameters used in the Beta-Poisson equation. Table 14 is presenting results from the factor sensitivity (FS) simulations. The minus sign at dose-response relationship for Norovirus is showing that if other α and β parameters were used the infection risk would be lower that the one found in the base line scenario. For *Campylobacter* and *Cryptosporidium* it is the opposite. If the other parameters or dose-response relationship from Table 4 would be used, the infection risk would be higher.

When using dose-response relationship it was discovered that if the incoming pathogen concentration was one or less the one, the result would tend to overestimate the infection risk. This was particular prominent for *Campylobacter*. This fact is not taken into account in the simulations and the infection risk can therefore be judged as conservative, especially for *Campylobacter.*

The annual infection risk was almost 200 times bigger when using the Beta-Poisson relationship than when using the exponential relationship for *Cryptosporidium*. By using different parameters in the Beta-Poisson relationship (suggested parameters from Table 4) for Norovirus the annual infection risk, using 95^{th} percentile, was decreasing from about 1.5 to about 0.004 infections per 10 000 persons and year. For *Campylobacter* the annual infection risk became 26 times bigger by using the other suggested parameters in the Beta-Poisson relationship.

The factor sensitivity analysis showed that it is of big importance to collect more data according to dose-response relationships since this relationship will have a big impact on the final result. The incoming concentration has also a big impact for the result. Therefore collection of reliable incoming concentration data is something to put focus on.

The results from using different methods for calculating disinfection showed that the biggest range of DEC variation was found for *Campylobacter*. Depending on method, baffling factor and start concentration the DEC value was varying between 3.81 and 366.82. For Norovirus the DEC value was varying between 2.27 and 116.33. Less sensitive for used method was *Cryptosporidium* with a DEC variation between 0.44 and 4.24. Data is gathered in Table 15. This shows that it is important to learn more about the disinfection.

Table 11. Results from simulations of infection risk and annual infection risk under base line conditions.

Statistic	Pathogen	Median	Mean	95 perc	97.5 perc	99 perc
P_{inf} (Infections)	*Cryptosporidium*	$7.53 \cdot 10^{-11}$	$8.02 \cdot 10^{-8}$	$2.79 \cdot 10^{-7}$	$8.02 \cdot 10^{-7}$	$1.72 \cdot 10^{-6}$
	Norovirus	$4.64 \cdot 10^{-8}$	$1.17 \cdot 10^{-7}$	$4.83 \cdot 10^{-7}$	$7.19 \cdot 10^{-7}$	$1.03 \cdot 10^{-6}$
	Campylobacter	$1.37 \cdot 10^{-10}$	$4.51 \cdot 10^{-10}$	$1.82 \cdot 10^{-9}$	$2.61 \cdot 10^{-9}$	$5.45 \cdot 10^{-9}$
Annual P_{inf} (Infections per 10 000 persons and year)	*Cryptosporidium*	0.000	0.293	**1.019**	2.929	6.285
	Norovirus	0.170	0.427	**1.764**	2.626	3.748
	Campylobacter	0.000	0.002	**0.007**	0.010	0.020

Note: Bold values showing the annual P_{inf} at 95th percentile and are the values that will be discussed.

Table 12. Maximal tolerable average concentration of each pathogen in the source water intake under base line conditions (column two) and under poorly treatment performance (column three). Concentration required (95th percentile) to cause one infection per 10 000 persons and year.

Organism	"Organisms"/l [a]	"Organisms"/l [b]
Cryptosporidium	0.031 [c]	0.0050
Norovirus	0.005	0.0008
Campylobacter	0.090	0.0130

Note: [a]Incoming concentration of organisms/oocysts that is acceptable at the inlet if the plant is operating under normal conditions. [b]Incoming concentration of organisms/oocysts that is acceptable at the inlet if the plant is operating under poorly treatment performance. [c]Without respect taken to the recovery factor. The simulation is performed for an illustrative purpose and the results does not necessary correspond to the reality. The values should therefore not be used separately or out of context.

Table 13. Additional annual infections per 10 000 persons and year for each simulated event of failure. See section 6.2.3 for data about the events. Result based on the 95th percentile.

Event	*Cryptosporidium*	Norovirus	*Campylobacter*
Potential process failure (R_1)	0.007	0.005	0.000
Breakthrough failure (R_2)	0.020	0.007	0.000
Disinfection failure (R_3)	0.000	0.033	0.004

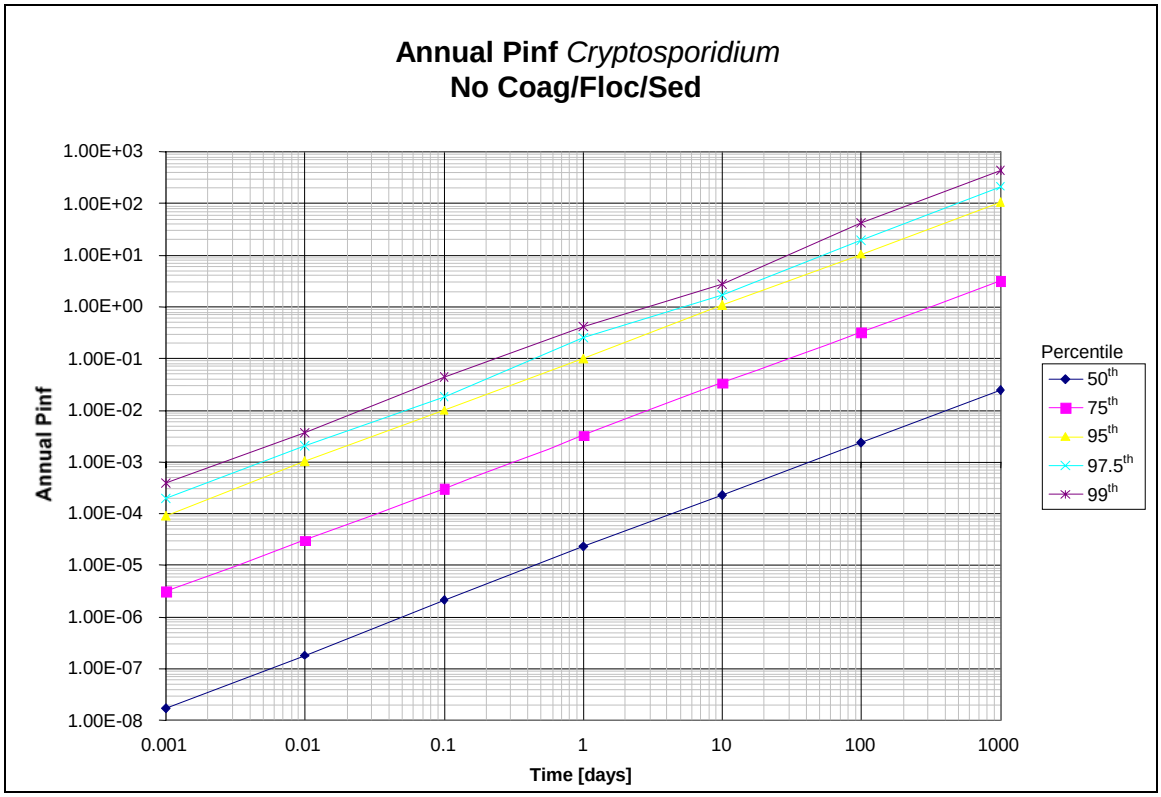

Figure 9. Critical duration for Cryptosporidium if the first removal step (R_1) in the WTP is failing.
Note: The figure is a infection-duration plot. X-axle is the time [days] with no coagulation, flocculation and sedimentation (R_1); all other parameters are held constant as in "base-line" condition. Simulations were made for 0.001 days to 1000 days. Y-axle is the annual P_{inf} (Infections per 10 000 persons and year). The different plots in the figure (the different colours) are results using different percentiles.

Table 14. Factor sensitivity (FS) table. Mutual relations between importances of stages. Simulations are made against base line scenario.

Stage	*Cryptosporidium*	Norovirus	*Campylobacter*
Source water	1.15	3.73	2.34
Coag/Foc/Sed	1.08	1.05	1.11
Filtration	1.35	0.83	1.52
Disinfection	0.57	2.24	3.89
Vol consumption	0.54	0.51	0.51
Dose-response	2.21	-2.54[a]	2.1

Note: [a]Minus sign showing that the if other suggested values are used the infection risk would be lower.

Table 15. Summary of disinfection (R3) variation (DEC values) depending on what kind of method, baffling factor and starting concentration that is used for the calculations. Ct values are based on flow data from LWTP. Since both temperature and flow data are taken from Lackarebäck the DEC values are valid specific for LWTP.

Source, method, BF and Concentrations, season.	DEC *Cryptosporidium*	DEC Norovirus	DEC *Campylobacter*
CSTR 1 tank, general[a]	0.57	2.43	3.89
CSTR 1 tank, summer[b]	0.87	2.74	4.04
CSTR 1 tank, winter[c]	0.44	2.27	3.81
First order equation, general[d]	1.18	116.33	-
BF[e] = 0.3, Conc(ClO_2)[f] = 1.0	2.02[g]	8.18[h]	303.26[i]
BF = 0.1, Conc(ClO_2) = 0.5	0.47[g]	4.16[h]	54.40[i]
BF = 0.7, Conc(ClO_2) = 1.0	4.24[g]	12.24[h]	366.82[i]

Note: [a]k value used in the CSTR equation varies with temperature. Simulations for k are made with general temperature data for one year based on data from Lackarebäck (Bergstedt, 2005). The yearly temperature variation is between 2.8 and 19.7 °C. [b]k value calculated with data from the three summer months in Sweden. Water temperature varies between 13.14 and 19.7 °C. The final result gives a DEC value valid for Lackarebäck during the summer. [c]k value calculated with data from the three winter months in Sweden. Water temperature varies between 2.8 and 4.6 °C. The final result gives a DEC value valid for Lackarebäck during the winter. [d]General k value is used, general temperature data for one year based on data from Lackarebäck (Bergstedt, 2005). [e]BF = Baffling Factor. [f]Conc(ClO_2) = start concentration of ClO_2. [g]Using equation from best fit, in vitro. DEC = 0.0164·(Ct)+0.126. Conditions pH 8, temp = 21 °C, Ct-range between 0 and 600 (Chaur *et al*., 2001). [h]Using equation for log removal proposed for ClO_2 disinfection based on feline calcivirus. Best fit from laboration. $Ln(N/N_o) = -k \cdot C_0^n \cdot (1-\exp(-nk't/m))^m \cdot (m/(nk'))^m$ Conditions, pH = 6, temp = 5.0 °C, valid in a Ct range of 20.20 - 30.30. k' = 0.03, k(a) = 1.59, n = 0.01, m = 0.52 (Thurston-Enriquez *et al*., 2004). [i]Assuming linear condition between 2 log reduction (Ct = 0.38) and 1 log reduction (Ct = 0.19). Valid for pH = 6.5, temperature = 15 °C (LeChevallier & Au, 2004).

8 Case Study Analysis

This chapter presents an analysis made on the case study. The first section will work as a background for the suggested HACCP-performance presented in the result section in Part Three. The section emphasis the differences between the water treatment plants and the food industry in the light of HACCP. The second and final section of the chapter presents important observations done during the performance of the QMRA at LWTP.

8.1 Analysis in the Light of HACCP

The initial product is one thing that differentiates the food and water industry. Within the food industry microbial contamination is expected to occur somewhere within the walls of the industry. For WTP the pathogens are already present when the raw water enters the plant. The result from the infection risk calculation in the QMRA can provide an input for making decisions about which pathogen should be considered in the performance of HACCP. It is a benefit to be able to make these judgments from "real" values such as infection risk instead of from hypothetical semi-quantitative values. The infection risk tells the decision-maker how many infections can be expected instead of just indicating that it can happen. One advantage of using QMRA is the fact that a decision must be made regarding what level of infection risk from drinking water a plant or a country is willing to accept.

In the question of CCP it might be easier within the food industry to find one CCP for each hazard (pathogen). Havelaar (1994) reported, for example, that a heating stage may be one CCP within the process that will eliminate all pathogens (microbial hazards). Previously, the chlorination could have been compared to the heating step. But since disease outbreaks do occur and since the chlorination process does produce by-products it is important to look at the whole treatment plant and increase the stage of important control points. For example the simulation showed that under normal base line conditions there was no significant risk of infection. But if the water intake was open (if water not passing Delsjön) the infection risk for Norovirus increased to an unacceptable level, even if there was a disinfection step later in the process for inactivation of Norovirus. In the food industry, the control within the plant can be more isolated. Requirement of good raw products can be expressed and therefore good raw products can therefore be expected. If using the definition of Critical Control Point (CCP) from the food industries, the catchmant area is not defined as a CCP since there exist one latter step that can control, eliminate or reduce the risk to an acceptable level. The Water quality depends both on the inactivation within the plant and the incoming water quality.

As a result from this one general conclusion can be made with the QMRA as a basis; source water protection could be a critical control point (CCP) for pathogens. With help from event infections and factor sensitivity analysis, judgment can be made about the importance of each step.

By combining results from calculations of infection risk under base line conditions, event conditions and the impact of duration of failure it should be possible to establish critical limits. Especially, the duration-infection figure could work as a good base for making judgment about the importance of failure and about how long time a failure can be acceptable. By performing hazardous event simulations it is possible to determine how many and which events that can be tolerated to occur. The critical concentrations can work as an aim when working with source water management.

8.2 Analysis of the QMRA Performance

Performance of a QMRA will provide a better understanding of the whole WTP. It will lead to identification of actual barriers and better understanding about lack of knowledge. It will also lead to learning about new scenarios and events.

At the moment there is a big limitation in existing data. All data comes with uncertainties. There is a big challenge in selecting distribution functions and in finding correct removal data and incoming concentrations. Result varies a lot depending on the dose-response relationship used.

One very important parameter in the QMRA is the disinfection step. The results from the sensitivity analysis investigating the variation of DEC values showed a great variation depending on which method that was used for calculating the disinfection. An important observation about disinfection at LWTP is that the calculation would be improved a lot if data about the chlorine dioxide concentration existed. Because measuring at LWTP are just made for chlorine residual it is hard to make good calculations. The chlorine residual is only measured at the end of the system. Preferred would be to know the ClO_2 concentration at the beginning of the disinfection step. Another important step for better disinfection calculation would be to understand the contact time. As established earlier, the contact time is a very important issue in the disinfection step. Better and secured contact time would improve the disinfection a lot and the uncertainties in the model would decrease.

Part 3 - Results and Discussion

9 Results

The main conclusion is that QMRA can be used as input to HACCP for water treatment plants (WTPs). However, there are some differences between the food industry and the WTPs and they must be taken into account when the HACCP is performed. Even if there are some low quality data in parts of the QMRA at a WTP it is still advantageous to perform it in order to acquire more knowledge about the system. The results from a QMRA can help to effectively direct and distribute resources and facilitate better management of the plant.

9.1 Performance of HACCP - Principle 1 and 2 - with Input from QMRA

This section describes how the two first HACCP-principles can be performed at a water treatment plant when results from a QMRA are used. Because extra focus is on development of critical limits, principle 3 (Establishing critical limits) will be dealt more thoroughly in its own section.

9.1.1 HACCP - Principle 1 - Hazard analysis

By using a guide such as "A Guide to Hazard Identification & Risk Assessment for Drinking Water Supplies" the first principle is straightforward and easy to undertake. Since water is universal and not plant specific it should not be necessary to additionally describe the product. What must been done is a description of specific conditions in the area which could have an impact on the water. This, however, is something that could be involved in the description of the plant and the surrounding area.

Before infection risk can be used as a basis for judgment, a decision about tolerated infection risk must be taken. There is as yet no generally agreed acceptable risk value in Sweden for water infections. However, the Dutch Drinking Water Degree required levels (one infection per 10 000 persons and year) can be used as reference value. Locally determined levels of risk can also be used. When the acceptable values are stated, the simulated infection risks from QMRA can provide information about which pathogen that must be prioritized and should be involved in the HACCP.

9.1.2 HACCP - Principle 2 - Determining critical control points

When making judgments about important control points the approach should be to look within the plant, as well as expanding the analysis so that it includes the catchment area. As a starting point the suggestion is to use each treatment step within the water treatment plant as an important control point. Also the point where the incoming water is entering the plant should be used. Results from a factor sensitivity analysis can work as input when making judgment about the most important process stages for each pathogen.

If the term Critical Control Point (CCP) is used the determination by decision tree should be changed so that even if there is a later treatment step for a specific pathogen an earlier stage in the process should still be able to be defined as CCP.

9.2 HACCP - Principle 3 - Critical Limits

Pathogen concentration is suggested as one basis for the establishment of a health-based critical limit. By calculating backward in the model, a critical incoming concentration that causes the infection risk that has been established as the acceptable one can be found. This

critical concentration can work as referent when making decision about what incoming concentration to aim for.

By using the acceptable level of infection, critical limits can be established by simulating different events and failures to see when the acceptable level is exceeded.

By performing event simulations as made in the case study the additional infection risk could be calculated for each event. These results give the operator good information about which events that have to be prioritized and how many of these events that can be tolerated before the level of acceptable infections is exceeded. Input data for events can be taken from SCADA data.

Graphs with infection rate plotted against duration of failure as made in the case study (see Figure 10) can work as a basis for judgment about how long time a failure can be tolerated. With help of graphs like this time limits for different failures or events can be established. The graphs are easy to monitor and tell the operator how many infections to expect when a process is failing.

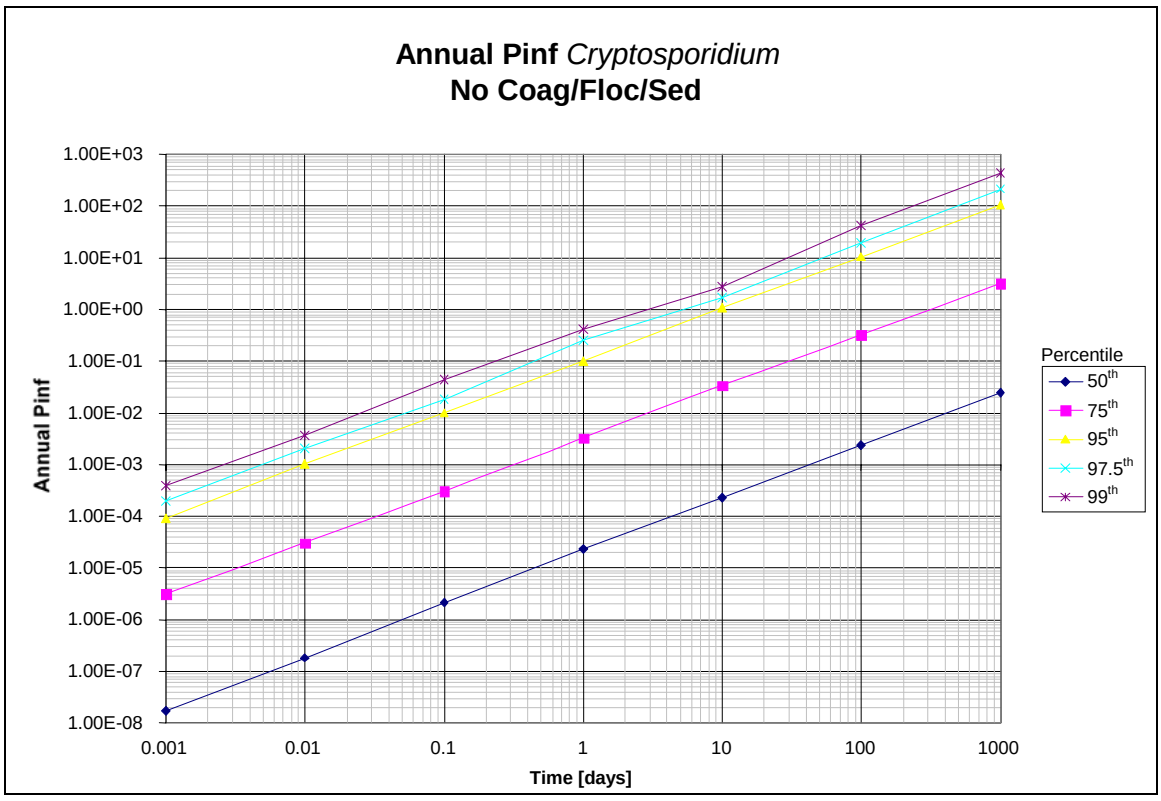

Figure 10. Annual infection risk from Cryptosporidium as a function of duration of failure in the first removal step (R_1) in the WTP. From graphs like this critical time limit can be determined.
Note: For detailed information about the figure please see chapter 7 and Figure 9.

10 Discussion

The overall purpose of this M.Sc. project was to evaluate and determine if and how QMRA can be used as a basis for an HACCP-style analysis in the water treatment industry. The aim was to describe how the three first HACCP-principles can be performed at a water treatment plant when results from a QMRA are used. Focus was particularly on how to develop critical limits. This chapter gives an overall discussion about the project and therefore focus is not limited to the result chapter.

The main issue when performing the simulations was the choice of data. It was very difficult to find and/or to know what kind of data to use. Much time was spent collecting data and attempting to determine which data being the most representative. What is most representative is not important in this project, however the same difficulties will be experienced by WTPs performing QMRA for HACCP. With all of the data, there were associated uncertainties and high variability. More about variation of inactivation data is found in Appendix B. The best way to address this problem is to, as far as possible, use data from similar treatment processes, and use distribution functions during the simulation. Obviously plant specific data are preferable. By collecting all of the data in a data system it is easy to improve the model and update simulations gradually when better data are received. However, not all WTPs have their own record data so it would be good to establish a database in which different water treatment plants could exchange data and knowledge with each other.

The issue of disinfection is a challenging part of the establishment of removal parameters. The large variation in DEC, depending on the determination method used clearly illustrates this issue.

The simulations showed that the results varied a lot depending on the dose-response relationship used. More work has to be done to find better dose-response relationships.

All simulations are based on the concept of "the best we can do". There are no recommended or pronounced ideas on how to use QMRA for HACCP performance but the approach taken in this project has been successful in terms of providing an input for further performance assessments. Even though data is lacking, the results of this study have shown that output from a QMRA can provide knowledge of the plant that can be used in the management of a WTP. For example this report has shown the importance of incoming concentration and the suggestion is that the industry should work on management of the catchmant area. By reducing events and using pre-removal stages, such as Delsjön, the removal within the WTP is not that critical and it should be possible to reduce the amount of chemicals within the industry.

One of the most notable observations made during research into the topic of HACCP was the diversity of definitions used. Critical control point, control point, event, hazard, hazardous event are all examples of terms that are frequently used. Before direct transfer of definitions and performance from the food industry to the WTP it is recommended that an additional analysis of the differences between the two industries is performed and the validity of straight transference is assessed.

One big issue in the performance of the QMRA and the HACCP-principles is that of Critical Control Points (CCPs). Here the choice was made to use each inactivation stage in the

process as an important stage and to involve the incoming water as an important parameter. There is still more that have to be done in the question of CCP. For example evaluating if there is a need to separate control point and critical control point within the water treatment plant. It appears that most control points within the water treatment plant are important for the end result and therefore it is recommended to evaluate if both critical control point and control point should be used jointly or if only one of them should be used. Within the frame of this project there has not been enough time to further evaluate the CCP concept. This is an open question that must be evaluated further.

One of the objectives in this project was how to develop critical limits when a QMRA approach is used in the water treatment industry. The outcome from this was suggestions on what critical limits can be based on. The suggestion of using hazardous events and failures as a basis for critical limits is new and, to my knowledge, a previously untried idea. Every water treatment plant has to develop its own limits depending on its acceptable infection risk and plant conditions such as incoming pathogen concentration and inactivation efficiency. The incoming concentration was also suggested as a basis for establishing critical limits.

The fact that a specific WTP was used for a case study does not have any effect on the suggestion on how QMRA should be used with the first three principles of HACCP. The performance should be the same for each water treatment plant. Using a different case plant would of course change the value of infection rate, time of failure and/or events to be simulated. However, the same conclusion would be found. Still it has been an advantage to perform the work based on one specific plant because the work has been straightforward and concrete.

The limitation of this project using only three pathogen indices does not compromise the reliability of the final results. Using different pathogens would of course have lead to different results of the simulations. However, the suggested course of action when performing the three first HACCP-principles would have been the same.

It should be remembered that the suggestions about HACCP performance made in this project are not to be considered as complete. More work has to be done in order to gain experience and widen the knowledge.

Finally, the fact that one inactivation step within the WTP can lead to increased risk, for example can the use of disinfection lead to by-products, makes the idea of minimizing the overall risk extra relevant for the water treatment plant. Therefore the hope is that the approach presented in this project is something that can both be used and work well in the future provided that it is further worked on and developed.

An additional use of this project is that it can act as a basis for further discussions about HACCP-principles within water treatment plants.

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Appendix A - Description of used pathogens

Protozoa-*Cryptosporidium*

The environmental stage of the organism *Cryptosporidium* is called *Cryptosporidium parvum* oocysts. C. *parvum* is resistant to free chlorine and chloramines and can survive in the environment for a long time. C. *parvum* causes diarrhea but can also be life threatening for weaker persons. (Clark *et al.,* 2003)

Virus-Norovirus

Norovirus also called Norwalk-like virus (NLV) is one of two members of the human calicivirus. It is a single-stranded RNA virus, about 30 nm in diameter. Like all enteric viruses in general, Norovirus is physicochemical stable and appear stable in the pH range between pH 2 - 9 and tolerate a heat up to 65 °C for 30 min. Previously outbreak caused by Norovirus have showed that the organism, just like protozoa, can survive under unfavourable conditions. Commonly symptoms that are reported are diarrhea and vomiting. (Thurston-Enriques *et al.,* 2003)

Bacteria-*Campylobacter*

Campylobacter jejuni and *Campylobacter coli* are the two most common *Campylobacter* species causing waterborne diseases for humans. The symptoms are mainly diarrhea combined with stomach pain. *Campylobacter* are identified as the most common causes of waterborne diseases in Sweden. (Andersson and Bohan, 2001; Westrell, 2004)

Appendix B - Variation of inactivation data

This appendix is written to illustrate the cumbersome issue about selecting removal data. Depending on what referent used, DEC can vary greatly. This section is not written to give a complete summary over the removal data but should instead be viewed as an illustration about different data that are available, how many parameters that are important and how much the result can vary depending on the data used.

There are many factors that can result in poor clarification in the process of flocculation, coagulation and sedimentation. Main factors emphasized in the literature are such as flow rate, poor or incorrect mixing of chemicals into the water, wrong dose of coagulant and bad slug removal (LeChevallier & Au, 2004). Studies have showed that pre-oxidation with chlorine or ozone have a positive impact on the particle removal of both sedimentation and filtration (Smeets, 2005; LeChevallier & Au, 2004; Hijnen *et al.,* 2005). Other parameters that can have an impact of the removal are pH, temperature, alkalinity, turbidity and amount of natural organic matter (LeChevallier & Au, 2004). Higher removal can be expected with a lower pH due to electrostatic forces on the surface of the colloids (of microorganisms) and the material in the filter (Hijnen *et al.,* 2005). A study made by Hendricks *et al.,* (1988) based on eight different water treatment plants came to the conclusion that the most important parameter that have an impact on the filtration is a correct coagulant. In the study they took coagulant, filtration mode, filter median and temperature (a range within 5 - 18 °C was studied) into account. With the exception for coagulation the other parameters did not significantly affect the quality of the filtration (LeChevallier & Au, 2004). A more recent study by Hass *et al.*, (2000) used *Cryptosporidium* when evaluating the most important factor/factors within the filtration step. The study included coagulation dose, pH, temperature, and mixing rate. Two conclusions were established. Apart from the fact that more research is needed, there was a clear statement of the importance of optimal coagulation dose for removal of *Cryptosporidium*. The filtration step is very efficient with an optimal coagulation dose but without proper coagulation the protozoa can pass the filtration process and the removal can be close to zero. (LeChevallier & Au, 2004)

Theoretically the range of removal through coagulation and flocculation are relative high for elimination of viruses, bacteria and bacterial spores and protozoan (Hijnen *et al*., 2005). But there are big differences and variations within the different groups of pathogens. For example the removal of viruses can vary greatly depending on what kind of coagulant being used. If aluminium is used as coagulant the removal can vary between 27 - 74 % depending on what kind of virus that is studied, see Table B1. Variation in removal between different bacteria has showed a range between 32 - 87 %. There are still problems to receive good and reliable data about the removal of protozoa. Two main reasons are, as mentioned earlier, that the amount of protozoa (for example *Cryptosporidium*) in the water is very low and that there are not many good methods to detect the pathogen in the water. (LeChevallier & Au, 2004)

Table B1. The variation of total DEC removal by filtration, depending on what virus that have been studied.

Virus	Removal range (DEC)
Bacteriophage MS2 and human enteric poliovirus	3.39 - 3.43
PRD-1 and enteric echovirus	1.15 - 1.53

Note: Removal with Aluminium as coagulant (LeChevallier & Au, 2004).

For *Cryptosporidium* and Giardia cysts a study showed that if right coagulation dose is used the removal can be as good as 2.3 log reduction. (LeChevallier & Au, 2004)

The disinfection removal can vary greatly depending on how the DEC value is calculated. Different simulations were made in the sensitivity analysis and the result is presented in Chapter 7. The simulation was made with equations found in the literature, calculations according to CSTR and also first order simulations. See Appendix F for different equations found for disinfection.

Appendix C - The Model

This short section concerns the model used in @risk. The purpose with this appendix is to give the reader an idée of how a model in @risk can look like. In parallel with the text following please see Figures C1 and C2 for better understanding.

Figure C1 shows a sheet displaying both in- and out data used in the model (this particular one is for *Cryptosporidium*). All pathogens have their own sheet. The "scenario column" in Figure C1 is where the data is written in to the model. The value can be point values or distribution functions.

The example (Figure C1) is a base line scenario for *Cryptosporidium*. The values for removal (R_1, R_2, R_3) are an average value in the figure. R_1 has a DEC value of 1.58 which is the average of a risk-function (RiskTriang(min;m.likely;max)), in this case: risktriang(0,5;1,54;2.7).

Disinfection (R_3) is referring to the disinfection calculations that are made in another Excel sheet (see Figure C2). The DEC values in Table C2 are connected with a lookup table containing different specific data for Lackarebäck. There are temperature variations for calculations of the k value. The temperature are divided into five groups; summer, winter, autumn, spring and one general for a whole year. When calculations are made @risk picks a value from one of theses groups, depending on what is chosen.

The lookup table also contains data such as cumulative Ct values that can be used if the disinfection calculations are performed with disinfection equations. These Ct values can be combined with different baffling factors. The cumulative Ct table is based on data from LWTP. The lookup table is not presented in this work.

As showed in the model (Figure C1) the results are presented as infection risk and annual infection risk for different percentiles.

Column four from the left (Figure C1) presents the result from the factor sensitivity (FS).

By setting up a simple model like this it is easy to make changes and perform new simulations when new data is obtained.

Calculation-forward

Data	Scenario	FS-indata	FS
Conc(C)0	0,04	0,60	1,15
Coag_R1	1,58	0,50	1,08
Filt_R2	1,35	0,00	1,35
DIS_R3	0,57	0,00	0,57
Rf(R1C*R2C)	2,93		
R(tot)	3,50		
Vol (L)	0,93	3,00	0,51
Result/output			
Dose	1,25E-05		
Pinf	5,02E-08		2,21
Pinf annual	0,18		

DOSE RESPONSE PARAMETER	
alfa	0,115
beta	0,176
k	238,6

percentile	Annual infection
0,1	0,00
0,5	0,00
0,75	0,03
0,95	1,11
0,975	1,75
0,99	6,55
Average	0,40

Days
365

Removal	5 percentil
R1	0,84
R2	0,89
R3	0,41
summa	2,14

percentil	individual Pinf
0,1	0,00E+00
0,5	5,61E-11
0,75	8,10E-09
0,95	3,04E-07
0,975	4,80E-07
0,99	1,80E-06
Average	1,09E-07

Figure C1. One sheet in the model. The numbers are in- and output values for a simulation.
Note: This is used for calculations with *Cryptosporidium*. This sheet is connected with other sheets for calculations of the disinfection, see Figure C2. For explanation of abbreviations and in data, see Part Two (Case Study) in this project.

equation		
k-value	k=A*e(-E/RT)	
CSTR 1	Ny/N(y-1)=1/(1+k*c*t)	
CSTR 2	Ny/N(y-1)=1/((1+k*c*t)/2)^2	
first order	Nt/N0=exp((-k)*Ct)	
	T	temp lookup table.
	t	time(lookup tabel*baffling)
	log(N/N0)	log-removal

Virus		
A	6,31E+08	
E	48350,96	
R	8,314	J/mol*K
		1K=273.16

	Virus	CSTR 1	CSTR 2		First order
	k(year)	6,68E-01			
	exampel				
yearly	Ny/N(y-1)	3,72E-03	5,49273E-05	Nt/N0	4,6841E-117
	DEC	2,43E+00	4,260211486	DEC	116,3293704
	k(summer)	1,347735			
	K(winter)	0,4594161			
Summer	Ny/N(y-1)	0,0018461	1,35823E-05	Nt/N0	1,5334E-235
	DEC	2,7337428	4,867027636	DEC	234,8143389
winter	Ny/N(y-1)	0,0053964	0,000115239	Nt/N0	9,04601E-81
	DEC	2,267892	3,938398675	DEC	80,043543

E.Coli		
A	501187,2	
E	23756	
R	8,314	J/mol*K
		1K=273.16

	E.Coli	CSTR 1	CSTR 2		First order
	k(year)	19,50532			
	Ny/N(y-1)	0,0001278	6,5292E-08	Nt/N0	0
	DEC	3,8935444	7,185139716	DEC	
	k(summer)	27,543827			
	K(winter)	16,232304			
Summer	Ny/N(y-1)	9,049E-05	3,27478E-08	Nt/N0	0
	DEC	4,0433994	7,484817368	DEC	
Winter	Ny/N(y-1)	0,0001535	9,42674E-08	Nt/N0	0
	DEC	3,8137826	7,02563863	DEC	

Crypto		
A	6,31E+08	
E	59087	
R	8,314	J/mol*K
		1K=273.16

	Crypto	CSTR 1	CSTR 2		First order
	k(year)	0,0067862			
	Ny/N(y-1)	0,2686381	0,179357613	Nt/N0	0,065711615
	DEC	0,5708323	0,746280185	DEC	1,182357857
	k(summer)	0,0160101			
	K(winter)	0,0042975			
Summer	Ny/N(y-1)	0,1347183	0,056381521	Nt/N0	0,001623941
	DEC	0,8705736	1,248863216	DEC	2,789429681
Winter	Ny/N(y-1)	0,3671005	0,288422427	Nt/N0	0,178342428
	DEC	0,435215	0,539970974	DEC	0,748745324

Figure C2. The sheet is used for disinfection calculations.

Note: For calculations of k temperature data, taken from LWTP, for a year is used. When calculations are made for contact time, data about flow is used from LWTP. Lookup table is another sheet that contains a big number of data. To be able to understand the abbreviations and words in this sheet it is necessary to read Part One and Part Two in this project. Ny/N(y-1) is the same expression as in eq. 7, i.e., Ni/N(i-1). The variation of DEC values are also presented in Chapter 7.

Appendix D - *@risk and statistics*

This appendix is a summary of @risk probability distribution functions used in this project. It is taken from the document "Risk Analysis and Simulation Add-In for Microsoft Excel (2004)". For detailed information about the statistics see "A Concise Summary of @RISK Probability Distribution Functions (2002)".

RiskGamma

Description: RiskGamma(alpha, beta) specifies a gamma distribution using the shape parameter alpha and the scale parameter beta.

For example: RiskGamma(0.081, 0.21) specifies a gamma distribution where the shape parameter has a value of 0.081 and the scale parameter has a value of 0.21.

Both alpha and beta must be greater than zero.

RiskLognormAlt

Description: RiskLognormAlt(arg1type, arg1value, arg2type, arg2value, arg3type, arg3value) specifies a lognormal distribution with three arguments of the type arg1type to arg3type. These arguments can be percentile values between 0 and 1.

In this case study the arg1value to arg3value are the consumption of cold tape water. The consumption is in l/day.

For example: Risklognormalt(10%, 0.4, 50%, 0.8, 90%, 1.6) specifies a lognormal distribution with a 10^{th} percentile of 0.4 l and a 50^{th} percentile of 0.8 l and a 90^{th} percentile of 1.6 l.

RiskTriang

Description: RiskTriang(minimum, most likely, maximum) specifies a triangular distribution with three points - a minimum, most likely and maximum. The direction of the "skew" of the triangular distribution is set by the size of the most likely value relative to the minimum and maximum.

For example: RiskTriang(0.5, 1.54, 2.7) specifies a triangular distribution with a minimum value of 0.5, a most likely value of 1.54, and a maximum value of 2.7.

The minimum value must be less than or equal to the most likely value. The most likely value must be less than or equal to the maximum value.

RiskUniform

Description: RiskUniform(minimum, maximum) specifies a uniform probability distribution with the entered minimum and maximum values. Every value across the range of the uniform distribution has an equal likelihood of occurrence.

For example: RiskUniform(10,20) specifies a uniform distribution with a minimum value of 10 and a maximum value of 20.

The minimum value entered must be less then the maximum value.

Appendix E - Discussion and presentation about used inactivation data

This appendix presents the course of action when choosing inactivation data. Because disinfection is discussed more thoroughly in the report focus is here on the two first inactivation steps, R_1 and R_2, in the model (coagulation-flocculation-sedimentation and filtration).

Removal data for these steps were based on a critical evaluation of a big series of removal data. The removal data was collected from an existing database (Hijnen *et al*., 2005). A smaller database with relevant data for the case study was then created so that data easily could be fetched and exchanged, see Table E1 and Table E2.

Simulations are made within the plant and it is not taken into account that there is a distribution system present. Even if the distribution system would be taken into account the outcome of the simulations would probably not be any different. There is a small amount (0.20 mg/l) of chlorine residual in the water that is leaving the plant and the measurement point in the end of the distribution system shows a surplus of approximately 0.08 mg/l chlorine residual. But since there is no mixing in the distribution system there is no guarantee that the Ct value will be able to cause a total log reduction and therefore the assumption is made that there is no reduction of pathogens in the distribution system. The concentration of residual in the distribution system has as purpose to obstruct microorganism growth.

In the original database, based on Hinjen *et al*., (2005), the data is weight in two different criteria; the scale of the study and the model organism that is used. This criterion is expressed as FSQ index, which is a quantitative number in the database that shows the importance of the data. DEC value multiplied with its FSQ index is presented as a DEC_FS value (see Table E1 and Table E2). By dividing the DEC_FS value with the total amount of FSQ a mean value for the removal is received. Similar calculations can be made for minimum, maximum and standard deviation. In this project mean value are calculated as described above which means that a lot of data is used as base.

For maximum value no data will be used with lower FSQ factor than 4. Minimum value will also be chosen depending on FSQ factors and feedback from expert opinion from LWTP. Filtration data is based on experiments with activated carbon (GAC). For illustrative purpose next section will show how data is chosen for *Cryptosporidium*. Similar method is used for the other index pathogens.

The approach - *Cryptosporidium*

Excel is calculating mean value from the database, based on a big range of studies. The highest value for sedimentation with FSQ-factor of 4 is DEC = 2.7. The lowest sedimentation value (FSQ = 5) is 0.5.

For active carbon filtration (GAC) available data is used. Even though the calculation is based on one referent the values seem to make sense when comparing them with literature and expert statements from LWTP. Data for GAC is in the database (Table E2) originally between 0 and 2.1 (decimal reduction). A judgment is made that zero removal is not representative for a normal condition at LWTP as they have 16 GAC-filtration filters and a policy that prevent breakthroughs. Therefore zero is excluded and the decimal reduction is instead between 0.7 and 2.1 with a mean value of 1.24.

Table E1. Inactivation data for the first treatment step (R_1) for Cryptosporidium. Data is taken from Hijnen et al., (2005) data base and the references in this table can be found in the original data base.

R1

Process 1	Process 2	Modelleded	Test.organism	Referens	FSQn	Experiment	DEC value	Lab/env	FSQ	Conditions	DEC_FS
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	3,70	lab	2		7,40
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 1998	2	2	3,30	lab	2	bench	6,60
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 1998	2	1	3,10	lab	2	bench	6,20
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 1998	2	3	3,10	lab	2	bench	6,20
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 1998	3	4	3,10	lab	3	pilot pl.	9,30
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	2,90	lab	2		5,80
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	2,80	lab	2		5,60
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	2,70	lab	2		5,40
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	2,70	lab	4	div.	10,80
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	2,60	lab	2		5,20
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	2,60	lab	4	div.	10,40
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 2001	3	1	2,50	lab	3	pilot pl.	7,50
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	2,40	lab	4	div.	9,60
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Kelley 1996	3	1	2,30		3		6,90
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	2,30	lab	3	pilot pl.	6,90
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	1	2,30	lab	4	div.	9,20
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	1	2,30	lab	4	div.	9,20
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	2,20	lab	3	pilot pl.	6,60
Flocculation	SED jar-test	Cryptosporidium	Cryptosporidium	Bell 2000	2	1	2,10	lab	2		4,20
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	2,10	lab	2		4,20
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	2,10	lab	3	pilot pl.	6,30
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	2,10	lab	3	pilot pl.	6,30
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	2,10	lab	3	pilot pl.	6,30
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	2,10	lab	4	div.	8,40
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	2,10	lab	4	div.	8,40
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	2,00	lab	2		4,00
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	2,00	lab	2		4,00
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 1998	3	4	2,00	lab	3	pilot pl.	6,00
Flocculation	LAM	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	1,90	lab	3	pilot pl.	5,70
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	1,90	lab	4	div.	7,60
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	1,80	lab	3	pilot pl.	5,40
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,80	lab	3	pilot pl.	5,40
Flocculation	LAM	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	1,70	lab	3	pilot pl.	5,10
Flocculation	DAF	Cryptosporidium	Cryptosporidium	Edzwald 2001	3	1	1,70	lab	3	pilot pl.	5,10
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,60	lab	3	pilot pl.	4,80
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,60	lab	3	pilot pl.	4,80
Flocculation	LAM	Cryptosporidium	Cryptosporidium	Edzwald 2001	3	1	1,60	lab	3	pilot pl.	4,80
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,60	lab	3	pilot pl.	4,80
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	1,60	lab	4	div.	6,40
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	1,50	lab	2		3,00
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,40	lab	3	pilot pl.	4,20
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,30	lab	3	pilot pl.	3,90
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,30	lab	3	pilot pl.	3,90
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	1,30	lab	4	div.	5,20
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	1	1,30	lab	4	div.	5,20
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	1,30	lab	4	div.	5,20
Flocculation	SED	Cryptosporidium	Cryptosporidium	States 1997	5	1	1,30	env	5	full-scale	6,50
Flocculation	SED	Cryptosporidium	Cryptosporidium	LeChevallier 1991	5	1	1,30	env	5	full-scale	6,50
Flocculation	SED	Cryptosporidium	Cryptosporidium	Edzwald 1998	2	1	1,20	lab	2	bench	2,40
Flocculation	LAM	Cryptosporidium	Cryptosporidium	Edzwald 2001	3	1	1,20	lab	3	pilot pl.	3,60
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,20	lab	3	pilot pl.	3,60
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	1,20	lab	3	pilot pl.	3,60
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	1,20	lab	4	div.	4,80
Flocculation	SED	Cryptosporidium	Cryptosporidium	Cornwell 2001	5	1	1,20	lab	5	div.	6,00
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	1,10	lab	4	div.	4,40
Flocculation	LAM	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	1,00	lab	3	pilot pl.	3,00
Flocculation	SED	Cryptosporidium	Cryptosporidium	Patania 1995	4	2	0,90	lab	4	div.	3,60
Flocculation	SED jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,80	lab	2		1,60
Flocculation	SED	Cryptosporidium	Cryptosporidium	Edzwald 1998	2	1	0,80	lab	2	bench	1,60
Flocculation	SED	Cryptosporidium	Cryptosporidium	Edzwald 1998	2	1	0,80	lab	2	bench	1,60
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	0,80	lab	3	pilot pl.	2,40
Flocculation	LAM	Cryptosporidium	Cryptosporidium	Edzwald 2003	3	1	0,80	lab	3	pilot pl.	2,40
Flocculation	SED	Cryptosporidium	Cryptosporidium	Kelley 1994	5	1	0,80	env	5	full-scale	4,00
Flocculation	SED jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,70	lab	2		1,40
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	0,70	lab	3	pilot pl.	2,10
Flocculation	SED jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,60	lab	2		1,20
Flocculation	SED jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,60	lab	2		1,20
Flocculation	LAM	Cryptosporidium	Cryptosporidium	Edzwald 2001	3	1	0,60	lab	3	pilot pl.	1,80
Flocculation	LAM	Cryptosporidium	Cryptosporidium	Edzwald 2001	3	1	0,60	lab	3	pilot pl.	1,80
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	0,60	lab	3	pilot pl.	1,80
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	0,56	lab	3	pilot pl.	1,68
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,50	lab	2		1,00
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,50	lab	2		1,00
Flocculation	SED	Cryptosporidium	Cryptosporidium	Kelley 1994	5	1	0,50	env	5	full-scale	2,50
Flocculation	DAF jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,38	lab	2		0,76
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	0,36	lab	3	pilot pl.	1,08
Flocculation	SED	Cryptosporidium	Cryptosporidium	Dugan 2001	3	1	0,26	lab	3	pilot pl.	0,78
Flocculation	SED jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,20	lab	2		0,40
Flocculation	SED jar-test	Cryptosporidium	Cryptosporidium	Plummer 1995	2	1	0,10	lab	2		0,20

SUM	237			
STD	0,88			
MEAN	3			
		STD		0,84

SUM	365,70

MEC(R1C)	1,54
MEAN	4,63
MAX	10,80
MIN	0,20
STD	2,54

MEC(R1C)/MEANFSQn	
MEAN	1,54
MAX	3,60
MIN	0,07
STD	0,85

Table E2. Inactivation data for the second treatment step (R2) for Cryptosporidium. Data is taken from Hijnen et al., (2005) data base and the references in this table can be found in the original data base.

R2

Process 1	Process 2	Modelleded	Test.organism	Referens	FSQn	Experiment	DEC value	Lab/env	FSQ	Conditions	DEC_FS
RSF	GAC	Cryptosporidium	Cryptosporidium	Patania 1995	3	1	0,8	lab	3		2,4
RSF	GAC	Cryptosporidium	Cryptosporidium	Patania 1995	3	1	1,1	lab	3		3,3
RSF	GAC	Cryptosporidium	Cryptosporidium	Patania 1995	3	1	2,1	lab	3		6,3
RSF	GAC	Cryptosporidium	Cryptosporidium	Patania 1995	3	2	0,7	lab	3		2,1
RSF	GAC	Cryptosporidium	Cryptosporidium	Patania 1995	3	1	2,1	lab	3		6,3
RSF	GAC	Cryptosporidium	Cryptosporidium	Patania 1995	3	1	0,9	lab	3		2,7
RSF	GAC	Cryptosporidium	Cryptosporidium	Patania 1995	3	2	1,5	lab	3		4,5
RSF	GAC	Cryptosporidium	Cryptosporidium	Patania 1995	3	1	0,7	lab	3		2,1

SUM	24			SUM 29,7
STD	0			
MEAN	3			MEC(R2C) 1,2375
		STD	0,59	MEAN 3,7125
				MAX 6,3
				MIN 2,1
				STD 1,78

MEC(R2C)/MEANFSQn	
MEAN	1,24
MAX	2,10
MIN	0,70
STD	0,59

Appendix F - Disinfection equations

During the performance of this project a smaller database was established containing data found about disinfection inactivation (see Table F1).

Table F1. Different equations found for disinfection.

n=number of experiments

OX=Oxidant demand-free system

NO= amount of inactivation not observed in actual experiment

Eq(1) lnN/N0=-kC0t^m*[(1-exp(-nk't/m))/(nk't/m)]

Disinfection	Modelleded	Test.organism	Referens	n	DEC value	Lab/env	FSQ	Conditions	DEC_FS	CT mg min /L	CT range	Notes	pH	Temp	Regression equation	R2	Equation	k'	k(a)	n	m
Chlorine	Norovirus	Feline calcivirus (a)	TE et al 2003	2	2	lab	2		4	1,55	0.25-3	(a)= aggregerat	7	5		0,94	LnN/N0=se eq(1)	0,05	4,26	-0,21	0,26
Chlorine	Norovirus	Feline calcivirus (a)	TE et al 2003	2	3	lab	2		6	8,47	5-10	(a)= aggregerat	7	5							
Chlorine	Norovirus	Feline calcivirus (a)	TE et al 2003	2	4	lab	2		8	29,06	NO	NO	7	5							
Chlorine	Norovirus	Polio virus type 1 (a)	TE et al 2003	2	2	lab	2		4	2,58	2.5-5.0	(a)= aggregerat	6	5		0,84	LnN/N0=se eq(1)	0,05	3,52	0,5	0,38
Chlorine	Norovirus	Polio virus type 1(a)	TE et al 2003	2	3	lab	2		6	7,6	7.5-22.5	(a)= aggregerat	6	5							
Chlorine	Norovirus	Polio virus type 1(a)	TE et al 2003	2	4	lab	2		8	16,36	7.5-22.5	(a)= aggregerat	6	5							
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	2	lab	2		4	0,02	<0.04	(d)=dissolved	6	5		0,95	LnN/N0=se eq(1)	0,18	0,07	-2,54	0,28
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	3	lab	2		6	0,07	0.04-0.08	(d)=dissolved	6	5							
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	4	lab	2		8	0,19	0.11-0.15	(d)=dissolved	6	5							
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	2	lab	2		4	0,05	<0.08	(d)=dissolved	7	5		1	LnN/N0=se eq(1)	0,03	232,59	1,04	1,64
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	3	lab	2		6	0,06	<0.08	(d)=dissolved	7	5							
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	4	lab	2		8	0,07	<0.08	(d)=dissolved	7	5							
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	2	lab	2		4	0,18	<0.32	(d)=dissolved	8	5		0,99	LnN/N0=se eq(1)	0,01	117,85	1,1	1,27
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	3	lab	2		6	0,23	<0.32	(d)=dissolved	8	5							
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	4	lab	2		8	0,27	<0.32	(d)=dissolved	8	5							
Chlorine	Norovirus	Polio virus type 1(d)	TE et al 2003	2	2	lab	2		4	0,93	1-2.75	(d)=dissolved	6	5		0,93	LnN/N0=se eq(1)	0,04	1,64	-1,17	0,28
Chlorine	Norovirus	Polio virus type 1(d)	TE et al 2003	2	3	lab	2		6	2,87	1.0-5.0	(d)=dissolved	6	5							
Chlorine	Norovirus	Polio virus type 1(d)	TE et al 2003	2	4	lab	2		8	6,36	10	(d)=dissolved	6	5							
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	2	lab	2		4	0,05	0.04-0.13		6	5		0,95	LnN/N0=se eq(1)	2,86	8,34	0,04	0,45
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	3	lab	2		6	0,11	0.09-0.17		6	5							
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	4	lab	2		8	0,22	0.17-0.34		6	5							
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	2	lab	2		4	0,15	0.04-0.17		7	5		0,99	LnN/N0=se eq(1)	0,19	55,55	1,31	0,43
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	3	lab	2		6	0,38	0.34-0.85		7	5							
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	4	lab	2		8	0,75	NO	NO	7	5							
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	3	2	lab	2		4	0,11	0.08-0.16		8	5		0,96	LnN/N0=se eq(1)	0,42	38,92	1,08	0,5
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	3	3	lab	2		6	0,17	0.16-0.23		8	5							
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	3	4	lab	2		8	0,24	0.16-0.23		8	5							
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	2	lab	2		4	0,21	0.09-0.36		8	15		0,84	LnN/N0=se eq(1)	0,24	16,6	0,76	0,43
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	3	lab	2		6	0,56	1.08-2.7		8	15							
Chlorine	Norovirus	Feline calcivirus (d)	TE et al 2003	2	4	lab	2		8	1.1(NO)	NO		8	15							
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	2	lab	2		4	1,51	0.72-2.4		8	15		0,96	LnN/N0=se eq(1)	0,15	3,09	-0,23	0,22
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	3	lab	2		6	9.69(N0)	NO		8	15							
Chlorine	Norovirus	Enteric Adenovirus (d)	TE et al 2003	2	4	lab	2		8	36.09(N0)	NO		8	15							
ClO2	Norovirus	feline calcivirus	TE et al 2005	5	4	lab	2		8	20.20-30.30			6	5			LnN/N0=se eq(1)	0,03	1,59	0,01	0,52
ClO2	Norovirus	feline calcivirus	TE et al 2005	4	3,6	lab	2		7,2	0,68		45.s	8	5				0,03	8,58	0,01	0,4
ClO2	Norovirus	feline calcivirus	TE et al 2005	4	4,2	lab	2		8,4	>4.2-<6.72		15.s	6	15				0,05	2,2	0,01	0,67
ClO2	Norovirus	feline calcivirus	TE et al 2005	3	4,15	lab	2		8,3	<18		15.s	8	15				0,07	167,01	0,01	2,17
ClO2	Norovirus	Enteric Adenovirus	TE et al 2005	2	4	lab	2		8	0.77-1.53			6	5			LnN/N0=se eq(1)	0,03	8,32	0,62	0,57
ClO2	Norovirus	Enteric Adenovirus	TE et al 2005	2	4	lab	2		8	0.80-1.59			8	5				0,04	362	6,01	0,6
ClO2	Norovirus	Enteric Adenovirus	TE et al 2005	2	4	lab	2		8	0.49-0.74			6	15				0,1	5,61	0,01	0,8
ClO2	Norovirus	Enteric Adenovirus	TE et al 2005	2	4,21	lab	2		8,42	<0.12		15.s	8	15				0,14	44,87	0,01	1,1
ClO2	Cryptosporidium	Cryptosporidium	Chaur et al 2001	1	2	lab	3	approx. value	6	1 000	0-1600	best fit, in vitro-MPN-cell	8	21	y = 0.0022x - 0.1444	0,995	y=DEC-removal x=ct				
	Cryptosporidium	Cryptosporidium	Chaur et al 2001		0,5	lab	3		1,5	200	0-1600	best fit, in vitro-MPN-cell	8	21							
ClO2	Cryptosporidium	Cryptosporidium	Chaur et al 2001	1	0,5	lab	3	approx. value	1,5	1 000	0-1600	In vitro	8	21							
ClO2	Cryptosporidium	Cryptosporidium	Chaur et al 2001	2	2	lab	3	approx. value	6	550	0-800	best fit, in vitro-MPN-cell	8	21	y = 0.0027x + 0.239		y=DEC-removal x=ct				
ClO2	Cryptosporidium	Cryptosporidium	Chaur et al 2001	2	2	lab	3	approx. value	6	75	0-600	best fit, in vitro-MPN-cell	8	21	y = 0.0164x + 0.126		y=DEC-removal x=ct				
ClO2	Cryptosporidium	B.subtilis spores	Chaur et al 2001	1	4,5	lab	2		9	75			8	21							
ClO2	Cryptosporidium	C.sporogenes spores	Chaur et al 2001	1	3,4	lab	2		6,8	50			8	21							
ozon	Cryptosporidium	Cryptosporidium	R.J.L et al 2000	1	2	lab	3		6	4	0-5	this is ekvations best fit.	7	20	y = 0.3535x + 0.1116	0,999	y=DEC-removal x=ct				
ClO2	Cryptosporidium	Cryptosporidium	R.J.L et al 2000	1	2	lab	3		6	100	0-100		8	20	y = 0.0188x + 0.0153	0,999	y=DEC-removal x=ct				
free Chlorine	Cryptosporidium	Cryptosporidium	R.J.L et al 2000	1	1	lab	3		3	2000	0-4000		6	20	y = 0.0007x + 0.1602	0,987	y=DEC-removal x=ct				
Chlorine	Bacteria	E.coli	White 1999		2							y=time [min], x=conc [mg]	8,5		y = 0.3213x-1.3932	0,999					
Chlorine	Bacteria	E.coli	White 1999		2							y=time [min], x=conc [mg]	7,5		y = 0.0022x-2.3168	0,997					
ClO2	Bacteria	E.coli	LeChevallier et al 1988		2					0,18		OX	6,5	20							
ClO2	Bacteria	E.coli	LeChevallier et al 1988		2					0,38		OX	6,5	15							
ClO2	Bacteria	E.coli	LeChevallier et al 1988		2					0,28		OX	7	25							

LUNDS UNIVERSITET

Informationsenheten, Box 117, Paradisgatan 5c, Byrålogen, 221 00 Lund
Telefon 046-222 12 34. Telefax 046-222 47 11