The use of water treatment SCADA data to quantify hazardous microbiological events and risks arising – A case study from Sweden

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Master's Thesis

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Abstract: As outbreaks of waterborne diseases caused by pathogenic micro-organisms still occur in developing as well as in developed countries, strategies for improving water quality can be expected to deliver substantial health gains. The overall objective of this MSc project was to critically evaluate the use of on-line monitoring data sets in quantitative microbial risk assessment (QMRA) and its implications for risk management for water treatment plants. This has been done by studying Supervisory Control and Data Acquisition (SCADA) data from Lackarebäck Water Treatment Plant in Gothenburg. By analysing SCADA data sets in parallel with diary records and deviation reports, the advantages and limits to the SCADA data in its ability to identify frequencies, duration and magnitude of hazardous events were assessed. The analysis showed that it was possible to identify possibly hazardous events by identifying deviations in turbidity, chlorine residual or pH SCADA data sets. SCADA systems have the potential for on-line identification of short term events that otherwise would have passed undetected. The duration of the identified events were, with few exceptions, all of short term ranging from 0.5 to 2.3 hours. By Cumulative Sum Control Charting (CUSUM) it was also possible to identify long term changes in water quality from the SCADA data sets. However, SCADA data sets don't provide information regarding all safety issues for the system and it is associated with a lot of uncertainties and should, hence, be seen as a compliment to traditional grab sampling rather than as a replacement.

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Summary

The primary objective of drinking water supply is to provide water that is safe for the public to drink. The microbiological quality of drinking water is maintained by selecting good quality source water, application of treatment processes in water treatment plants and protection of distribution system. To assure that water treatment processes works properly they are monitored in real time by online control and monitoring systems, that is Supervisory Control and Data Acquisition (SCADA) systems. On a regular basis these systems collect parameters such as flow, turbidity, pH, disinfectant residuals and temperature along the production line. Although these measures of process performance cannot be directly translated into pathogen removal, they can still prove to be a valuable source of information for undertaking assessments of risks.

The overall objective of this MSc project was to critically evaluate the use of SCADA parameter data sets with a view to using them in Quantitative Microbial Risk Assessment (QMRA) and their use for risk management of water treatment plants.

The overall method to reach the objectives was to pursue a literature study followed by a case study. The literature study was undertaken to survey similar previous work and to cover other relevant theory. The case study was undertaken to address the problem on a real case using Lackarebäck Water Treatment Plant as a case study.

As outbreaks of waterborne diseases caused by pathogenic micro-organisms still occur in developing as well as in developed countries, strategies for improving water quality can be expected to deliver substantial health gains (WHO, 2005). A new risk based approach, the Safe Water Framework, has been introduced by the World Health Organization as a new strategy for the provision of water that is safe to drink (Fewtrell & Bartram, 2001). The Safe Water Framework is an iterative methodology where risk assessment along with specified health targets will constitute the basis for risk management. The proposed way to undertake the risk assessment is by QMRA whereas the risk management is proposed to rely on a management system named the Water Safety Plan including the management tool Hazard Analysis and Critical Control Point (HACCP). The rationale of HACCP is to control hazards at the time of manufacture rather than trying to detect problems by testing the end product. The method is based upon identification of each step within the process that can be crucial regarding to the safety and thereafter the taking of corrective action to reduce the risks.

By tradition, quantification of microbial risks in the water community has been made on the basis of grab sampling and epidemiology. This method has generally resulted in drinking water of high quality but has over the years showed some shortcomings (Medema & Smeets, 2004). To manage these shortcomings QMRA has been proposed as the new way to assess risks in the water community (WHO, 2004). The objective of QMRA is to identify and quantify the risk of infections. To quantify risks – frequencies and magnitudes of hazardous events must be measured. A hazardous event is defined as an incident or situation that can contribute to the presence of a hazard where a hazard is a biological, chemical or physical agent that has the potential to cause harm and/or give rise to water quality which is unacceptable for consumers (Nadebaum *et al.,* 2004).

LeChevallier & Au (2004) and WHO (2004) propose that health effects associated with pathogens tend to be due to short-term rather than long-term exposure. Westrell *et al* (2003) state that it is clear that it is under normal conditions and not during failures, that most infectious matter bypasses the treatment. A starting point for this thesis has been that managing small undetected events can be an efficient way of reducing health risks.

SCADA data systems are commonly used in the water supply industry (Scott *et al.,* 1999). These systems automatically collect and store data at short intervals and are, in theory, suitable as inputs for QMRA. There do not seem to be any standards for undertaking analysis of the sampled data for this purpose. Time series analysis is a methodology to understand time series such as those generated by SCADA systems. Control charting and Cumulative Sum Control Charting (CUSUM) analysis are both well proven industry quality control methods and applicable to SCADA data sets. This thesis explores how those methods can contribute to QMRA.

Göteborg Water and Wastewater Works supply drinking water in the Gothenburg area. Göta älv is being used as the source water and the drinking water is produced at Alelyckan and Lackarebäck Water Treatment Plants. The treatment processes include coagulation, sedimentation, granulated active carbon filtration and disinfection. The process is monitored by SCADA systems. Diary records are taken on a daily basis and cover day to day issues such as general observations, maintenance and small incidents. Major events that could have an impact on the overall process performance are recorded in deviation reports.

By analysing diary records and deviation reports parallel with SCADA data sets, advantages and limitations of SCADA in its ability to identify frequencies, durations and magnitudes of events, could be proved. 10-minute mean values for the time period 01/Oct/2004 to 19/Sep/2005 were compiled. The following parameters were considered being of possible relevance for microbial quality:

- Turbidity in raw water
- Turbidity in filtrate water
- Turbidity in drinking water
- Chlorine residual in raw water weir
- Chlorine residual in drinking water
- pH in flocculation chamber one

These parameters were studied and events were identified and compared to adjacent diary records and deviation reports. In total 119 events were identified and classified. 71 % were classified non-hazardous whereas the other 29 % were classified possibly hazardous. Of those classified non-hazardous, 85 % were the result of maintenance and 15 % the result of incidents. Of those classified possibly hazardous, 76 % were of unknown cause and 24 % were caused by maintenance or incidents. Those events classified possibly hazardous were further quantified. The duration of identified possibly hazardous events, with few exceptions, ranged between 0.5 and 2.3 hours. Different SCADA data time series differed greatly in appearance mainly due to seasonal variations and inherent variability. CUSUM proved to be able to detect long term trends such as possible algae bloom or adjustment of dosing levels. The classification and quantification of the events as above were based upon

119 events. Still, it is to be seen as a preliminary broad outline classification which is not strictly scientifically underpinned. However, due to the high number of events, uncertainties associated with the classification and quantification of the events were likely to only have a minor impact on the results.
The results show that it was possible to estimate frequencies, durations and magnitudes for events as well as statistics for baseline conditions. The identification and quantification of events and the analysis of corresponding diary records and reports were time demanding if not undertaken in a systematic way.

Overall positive attributes to SCADA are:

- SCADA data is a good source from which to identify potential hazardous events that otherwise might have passed without detection
- SCADA systems have the potential for on-line event identification which enables a quick response from the operator when an event is at hand
- SCADA analysis adds knowledge about the system and "knowing your system" is a prerequisite for undertaking assessments of risks
- SCADA analysis generates numerical data suitable for QMRA

Disadvantages about SCADA are:

- SCADA systems are not likely to detect all events and should, hence, be seen as complimentary to grab sampling and laboratory tests
- SCADA data does not say everything about your system and can thus lull the management into a false sense of safety
- SCADA analysis is to a great extent dependent on accurate diary records
- The use of SCADA data is associated with a lot of uncertainties

More research of the use of SCADA data for microbial risk assessment for water treatment plants needs to be carried out before the methodology can be applied generally. This initial analysis showed that one value of SCADA data lies in its ability to identify and provide estimates of duration of potential hazardous events.

Recommendations coming out from this study are:

- For further research
  - Studies about how different SCADA parameters are relevant to microbial risk should be pursued
  - Studies on the extent of deviation that could contribute to microbial risk should be pursued
  - Studies about where to locate SCADA data measuring points relevant for microbial risk should be pursued
  - Studies about SCADA systems ability for on-line event identification should be pursued on a set of different water treatment plants
  - The use of CUSUM or other statistical process control methods should be further studied on a variety of SCADA data sets from water treatment plants
  - On-line monitoring should be integrated with HACCP

- For management of water treatment plants
    - Diary records with time reference provide useful information for event identification and should be recorded continuously
    - To further reduce the size of SCADA data sets, one option might be to process the data and keep high resolution data during periods of deviation and low resolution data during normal (optimal) conditions
    - SCADA data collected during cleaning, maintenance or during periods with unrepresentative monitoring should be annotated, preferably by direct crosslink to electronic diary

Sammanfattning

Det primära målet för dricksvattenförsörjning är att förse allmänheten med vatten som är säkert att dricka. Den mikrobiologiska kvaliten för dricksvatten upprätthålls genom att välja bra dricksvattentäkter, rena vattnet i vattenverk och slutligen genom att skydda distributionsnätet från intrång. För att försäkra att vattenreningsprocesserna fungerar övervakas dessa i realtid av kontroll- och mätutrustning benämnd SCADA (Supervisory Control and Data Acquisition). På regelbunden basis samlar dessa system in data som flöde, turbiditet, pH, disinfektionsöverskott och temperatur längs med produktionslinjen. Dessa mått av processprestanda kan inte direkt översättas till patogenavskiljning. Emellertid kan de utgöra en värdefull källa av information för att utföra kvantiativa riskbedömningar.

Syftet med detta examsarbete var att kritiskt utvärdera nyttjandet av SCADA-data i kvantitativ mikrobiell riskbedömning (QMRA) och i riskhanteringsprocessen som sådan för vattenreningsverk.

Arbetet utfördes genom dels en litteraturstudie och dels en fallstudie. Litteraturstudien genomfördes för att kartlägga tidigare arbete inom området och för att täcka relevant teori för fallstudien. Fallstudien på Lackarebäck Vattenreningsverk i Göteborg genomfördes för att adressera problematiken på ett riktigt fall.

Utbrott av vattenburna sjukdomar orsakade av patogena mikroorganismer inträffar alltjämt i såväl i- som u-länder. Strategier för att förbättra vattenkvaliten kan således antas resultera i betydande hälsovinster (WHO, 2005). En ny riskbaserad ansats, the Safe Water Framework, har introducerats av Världshälsoorganisationen som en ny strategi för att trygga tillförseln av säkert dricksvatten (Fewtrell & Bartram, 2001). The Safe Water Framework är en iterativ metodik där riskbedömning och specificerade hälsomål skall utgöra grunden för riskhanteringsprocessen. Den av Världshälsoorganisationen föreslagna vägen att utföra riskbedömning är genom QMRA. Riskhanteringsprocessen kommer att bygga på ledningssystemet the Water Safety Plan vilket också inkluderar Hazard Analysis and Critical Control Point (HACCP). HACCP är ett verktyg för riskanalys och kontroll av risker under tillverkning av en produkt. Genom att identifiera faktorer som kan påverka produktens kvalitet under tillverkningen snarare än genom att testa slutprodukten kan risker förknippade med produkten minimeras.

Av tradition har kvantifiering av mikrobiella risker inom vattenreningssektorn utförts genom stickprov och epidemiologi. Denna metod har oftast resulterat i dricksvatten av hög kvalitet men den har också visats sig ha en rad brister (Medema & Smeets, 2004). För att komma tillrätta med dessa brister har QMRA föreslagits som en ny metod att identifiera och kontrollera risker i vattenreningssektorn (WHO, 2004). Målet med QMRA är att identifiera och kvantifiera risk för infektion. För att kvantifiera risk måste frekvens och storlek av farliga händelser mätas. En farlig händelse definieras här som en incident eller ett förhållande som kan bidra till närvaro av en fara där en fara är en biologisk, kemisk eller fysisk agent som har potential att skada eller ge upphov till för konsumenter oacceptabel vattenkvalitet (Nadebaum *et al.,* 2004).

LeChevallier & Au (2004) och WHO (2004) är av uppfattningen att hälsorisker associerade till patogener i dricksvatten orsakas av korta snarare än långa genombrott av patogener i dricksvattenverk. Westrell *et al* (2003) fastslår att det är under normala förhållanden och inte under fel på anläggningen som genombrott av patogener sker. Utgångspunkt för detta examensarbete har varit att identifikation av korta, tidigare icke detekterade, händelser kan vara ett effektivt sätt att reducera hälsorisker.

SCADA-system är vanligt förekommande inom vattenreningssektorn (Scott *et al.,* 1999). Dessa system samlar och lagrar automatiskt och regelbundet data och är, i teorin, lämpliga som källa för ingångsdata till QMRA. Det verkar inte finnas några standarder för att utföra analyser för detta syfte. Tidsserieanalys är en metodik för att förstå tidsserier såsom de genererade av SCADA-system. Styrdiagram eller tidsserieranalys likt CUSUM är båda välbeprövade standardmetoder inom industrin för kvalitetssäkring och tillika tillämpbara på SCADA-data. Detta examensarbete syftar till att uforska hur dessa metoder kan bidra till QMRA.

Göteborg Vatten- och Avloppsverk förser göteborgsregionen med dricksvatten. Som dricksvattentäkt används Göta älv och dricksvattnet produceras vid Alelyckan och Lackarebäck vattenreningsverk. Reningsprocessen inkluderar koagulering, sedimentering, snabbfiltrering genom aktivt kol och desinfektion. Processen övervakas av SCADA-system. Information om drift och eventuella störningar loggas i en elektronisk dagbok. Dessa noteringar täcker allmän drift såsom generella observationer, underhåll och små incidenter. Större incidenter som kan ha allvarlig påverkan på processprestanda bokförs i avvikelserapporter.

Genom att analysera dagböcker och avvikelserapporter parallellt med SCADA-data, kunde fördelar och svagheter med SCADA-data som underlag för att beskriva frekvens, varaktighet och storlek av farliga händelser beskrivas. 10-minuters medelvärden av SCADA data för tidsperioden 01/Oct/2004 to 19/Sep/2005 sammanställdes. Följande parametrar ansågs vara av möjlig relevans för mikrobiell kvalitet:

- Turbiditet i råvatten
- Turbiditet i filtrat
- Turbiditet i dricksvatten
- Kloröverskott i råvattensnäcka
- Kloröverskott i dricksvatten
- pH i flockningskammare ett

Dessa parametrar studerades och händelser indentifierades och jämfördes med dagböcker och avvikelserapporter. Totalt identifierades och klassificerades 119 händelser. 71 % klassificerades som icke farliga händelse och 29 % klassificerades som eventuellt farliga händelser. Av de klassificerade som icke farliga, var 85 % orsakade av underhåll och 15 % resultatet av incidenter. Av de klassificerade som eventuellt farliga, var 76 % av okänt ursprung och 24 % var orsakade av möjligt underhåll eller av incidenter. Händelser som ansågs vara eventuellt farliga kvantifierades ytterligare. Varaktigheten av identifierade eventuellt farliga händelser varierade, med få undantag, mellan 0.5 och 2.3 timmar. Tidsserier av SCADA-data varierade kraftigt i utseende. Detta var främst beroende av säsongsvariation samt inneboende variabilitet. CUSUM identifierade långtidsförändringar som möjlig

algblomning och justering av doseringsnivåer. Klassificeringen och kvantifieringen av händelserna baserades på 119 händelser. Emellertid skall klassificeringen ses som en första grovanalys där indelningen inte är strikt vetenskapligt underbyggd. Tack vare det stora antalet undersökta händelser kan osäkerheter förknippade med klassificeringen och kvantifieringen antas ha ringa betydelse för resultatet.
Resultatet visar att det är möjligt att uppskatta frekvenser, varaktighet och storlek för händelser såväl som statistik för normala förhållanden (baslinje). Identifikationen och kvantifieringen av händelser samt analysen av tillhörande dagboksanteckningar och avvikelserapporter var tidskrävande om den inte utfördes på ett systematiskt sätt.

Fördelar med SCADA är:

- SCADA-data är en god källa för information för identifikation och kvantifiering av händelser som annars troligen inte upptäckts
- SCADA-system har potential för att identifiera händelse on-line och således möjliggöra snabba avhjälpande eller skadebegräsande åtgärder
- SCADA-analys tillför kunskap om hur systemet uppträder och detta är en förutsättning för riskanalys
- SCADA-analys kan tillhandahålla kvantitativa data lämpliga för QMRA

Nackdelar med SCADA är:

- Nyttjandet av SCADA-data är behäftat med många osäkerhetsfaktorer
- SCADA-data tillhandahåller inte information om alla farliga händelser, och skall således beaktas som ett komplement till traditionella stickprov och laboratorietest
- SCADA-analys tillhandahåller inte information om alla faktorer som rör säkerhet och kan således invagga ledningen i en falsk känsla av trygghet
- SCADA-analys är i stor utsträckning beroende av kompletterande dagboksanteckningar

Mer forskning kring nyttjandet av SCADA-data för mikrobiell riskbedömning för vattenreningsverk måste utföras innan metodiken kan tillämpas generellt. Denna inledande analys visade att ett värde med SCADA-data ligger i dess förmåga att identifiera och utgöra underlag för kvantitatifiering av potentiellt farliga händelser.

Rekommendationer från denna studie är som följer:

- För framtida forskning
  - Studier bör syfta till att undersöka olika SCADA-parametrars samband med mikrobiell risk
  - Ytterligare studier av vid vilken nivå som avvikelser blir signifikanta för mikrobiell risk måste utföras
  - Framtida studier bör syfta till att undersöka var SCADA-mätpunkter relevanta för att mäta mikrobiell risk ska placeras
  - Studier bör undersöka SCADA-systems förmåga att identifiera händelser on-line på olika vattenreningsverk
  - Nyttjandet av CUSUM och andra metoder för tidsserieanalys bör undersökas ytterligare på olika dataserier från vattenreningsverk
  - On-line-mätning bör integreras med HACCP

- För ledning av vattenreningsverk
    - Dagboksnoteringar med tidsreferens tillhandahåller användbar information för identifikation av farliga händelser och kan med fördel föras på regelbunden basis
    - Genom att processa insamlad SCADA-data och spara data med högre upplösning under avvikelser och lägre upplösning under normala eller optimala förhållanden kan datamängder minskas
    - SCADA-data mätt under rengöring, underhåll eller under perioder med suboptimal eller ickerepresentativ mätning bör märkas, företrädesvis genom att koppla den elektroniska dagboken med SCADA-datan

Contents

1 Introduction

1.1 Background

The primary objective of drinking water supply is to provide water that is safe for the public to drink. Pathogenic micro-organisms in drinking water can have a major impact on health (Medema & Smeets, 2004). Outbreaks of waterborne diseases still occur in developing as well as in developed countries. Hence, strategies to improve water quality can be expected to deliver substantial health gains (WHO, 2005).

The microbiological quality of drinking water is maintained by selecting good quality source waters, application of treatment processes in water treatment plants, and protection of the distribution system. As urban drinking water from a water treatment plant is generally supplied to numerous consumers it is also a system at risk since a system failure at the water treatment plant can affect many people.

To assure that treatment processes work as intended they are monitored in real time by complex online control and monitoring systems, that is SCADA systems. On a regular basis these systems collect process performance data including parameters such as flow, turbidity, pH, temperature, chlorine and other disinfectant concentrations, particle size profile, conductivity, and oxygen.

Although a measure of process performance cannot always be directly translated to pathogen removal it can still prove to be a valuable source of information. For example, spikes in turbidity may indicate periods of poor performance (Petterson *et al.,* 2004) which in turn may be used as an indicator of hazardous events. SCADA monitoring might be useful for identifying hazardous events and control microbial quality and risk. To minimise the effect of microbial hazards these parameters could be more extensively studied and used as a basis for risk management. However, the use of SCADA to estimate pathogen removal and hence detect hazardous events from process performance is a methodology that has not been fully explored.

Microrisk is a European Commission funded research project that aims to develop strategies to improve water quality. The Microrisk project consists of eight work packages, and will result in a final harmonized risk assessment framework (The Microrisk consortium, 2006). This thesis has been undertaken in close relation to Microrisk *Work Package 6: Risk assessment & uncertainty analysis* and to the Master's Thesis *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* by Rebecka Thorwaldsdotter (2006).

1.2 Objectives

The overall objective of this MSc project was to critically evaluate the use of SCADA parameter data sets with a view to using them in Quantitative Microbial Risk Assessment (QMRA) and their use for risk management of water treatment plants.

The process developed to undertake this work was:

1. Review available SCADA information
2. Identify data that might be relevant to pathogen control
3. Develop criteria for identifying events
4. Compute frequency, duration and magnitude of events
5. Document uncertainties associated with the use of SCADA monitoring
6. Evaluate possible use in QMRA modelling

1.3 Overall method

The overall method to reach the objectives was to pursue a literature study followed by a case study.

The literature study, Part one, was undertaken to survey similar previous work and to cover other relevant theory. This included studies of WHO Drinking Water Guidelines and Harmonised Framework, Quantitative Microbial Risk Assessment (QMRA), Microrisk, water treatment, hazards, SCADA monitoring and time series analysis. Each chapter is introduced with a brief summary discussing the connection to the project overall objectives.

The case study, Part two, was undertaken to address the problem on a real case using LWTP as a case study. The aim of this study was not primarily to identify those incidents or situations that can contribute to the presence of a hazard at LWTP, but rather to determine if SCADA data can be used as an input to QMRA generally. However, the case study must provide real events to be of value to study. This leads us to the question why was LWTP chosen as a case study? QMRA has shown that it is clear that source water quality at off-takes greatly influences the end risk to the consumer and that there is a very large difference in microbiological quality of river and reservoir water (Roser, 2005). It appears that AWTP is at much higher risk due to absence of a reservoir, and therefore, it should in theory provide a good example to study. Although there is as much SCADA data from AWTP as for LWTP, it is less readily available from the latter at this time due to a major SCADA system upgrade (Bergstedt, 2005). Hence, problems with data access made AWTP unsuitable for a study at this time. LWTP is unique in that way it is one of very few water treatment plants that have been found to have an electronic diary and deviation report as well as organized and accessible SCADA data sets (Roser, 2005). Consequently, LWTP has been chosen as a case study because of the openness and the ability to export data including high resolution SCADA, diary records and deviation reports. Even though LWTP is considered to be a clean system with very few deviations or incidents, the microbial risk is an issue at present treatment (Bergstedt, 2005). Part two gives an introduction to LWTP, states the used methods and the results of the study. The part is finished with a discussion of the results of the case study.

Finally, in Part three, the findings from the literature study and the case study were compiled and discussed. This part is finished with further recommendations.

1.4 Limitations

The study focus was on SCADA parameters from LWTP. The catchment area and the distribution system were considered to be beyond the focus of the project. Within the SCADA data sets the focus was on those relating to pathogen control. This included sets collected for nominally other purposes which were considered likely to influence microbial risk. SCADA data was provided for an approximate year (01/Oct/2004-19/Sep/2005). Hence, the study comprised data for this period of time.

Part one – Literature review

2 Risk management

A new risk based approach has been proposed for the provision of safe drinking water (WHO, 2004). This chapter provides an introduction to the current status of the risk based approach as well as proposed improvements. Various developments including Drinking Water Guidelines, Safe Water Framework, Quantitative Microbial Risk Analysis (QMRA), Microrisk, Water Safety Plans (WSP) and Hazard Analysis and Critical Control Point (HACCP) are introduced.

2.1 WHO Drinking Water Guidelines and harmonised 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 harmonised framework assessing the health risks associated with exposure to health hazards through water. WHO advocates that a risk based iterative approach with embedded quality targets should be used. As the prerequisites are likely to change, risk assessment and risk management is an ongoing iterative process. A framework, named *Safe Water Framework*, is depicted in its simplest form in Figure 1. (Fewtrell & Bartram, 2001)

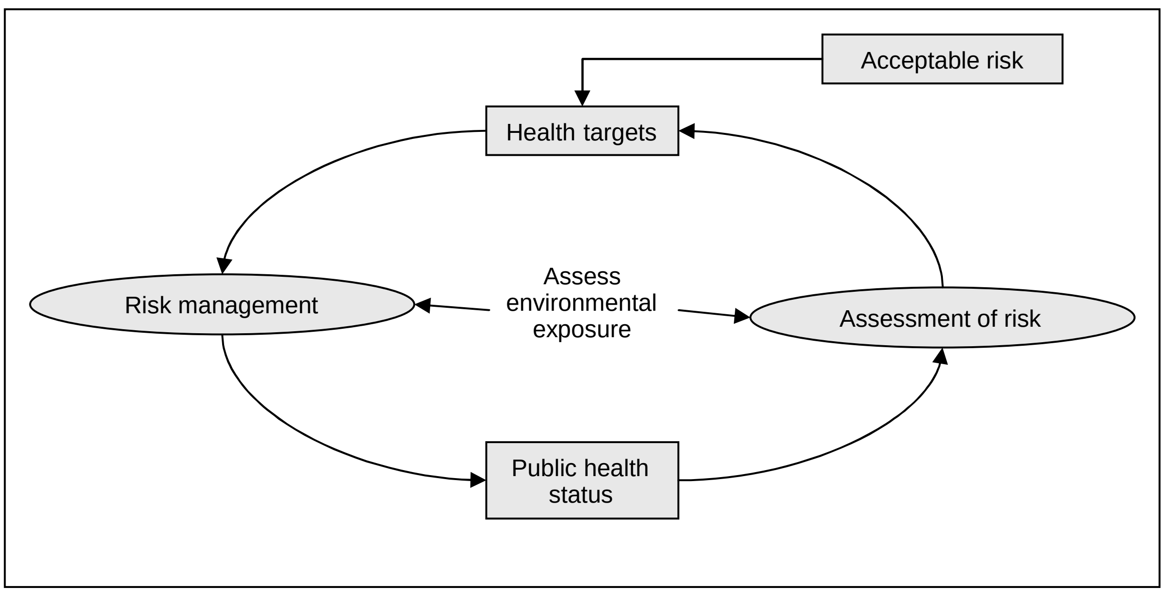

Figure 1. Safe Water Framework (Fewtrell & Bartram, 2001)

2.1.1 Assessment of risk

For the WHO 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, which can be translated to the risk of infection. One objective has been to reflect the health concerns for vulnerable groups such as children and the old. The endpoint for this assessment has been proposed to be a common exchange unit such as Disability Adjusted Life Years (DALYs).

The assessment of risk is a starting point for the harmonised 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 partly a formal component in the risk assessment (see Chapter 2.2) and, in this case, partly an important input to the risk management. The environmental exposure assessment aims to prioritize among potential interventions. For example, if the pathogen exposure mainly occurs from a non-water related source, it might be of no or insignificant benefit trying to prevent routes of infection through drinking water. (Fewtrell & Bartram, 2001)

2.1.3 Acceptable risk and health targets

Acceptable risk and the outcome of assessment of risk underlie 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. 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).

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 for example process performance can be used to ensure the target values are achieved. The monitoring should be designed to deal with short and long term events as well as for background rates. 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 Hazard Analysis and Critical Control Point (HACCP) used in the food industry. (Fewtrell & Bartram, 2001)

2.1.5 Public health status

To ensure that measures being put into place have the desired effect a survey of the public health must be undertaken. The public health outcome is ascertained by the normal health surveillance system and quantified by QMRA, as described by Fewtrell & Bartram (2001) and WHO (2004). The public health outcome provides support that the quality targets defined during the risk management process are adequate (Fewtrell & Bartram, 2001). Measuring the public health status and undertaking QMRA should not be seen as an endpoint, but rather as a basis for selecting further risk assessments.

2.2 Quantitative Microbial Risk Analysis (QMRA)

QMRA is the method proposed to undertake assessment of risk in the WHO harmonised framework (WHO, 2004). By tradition, quantification of microbial risks in the water community has been made on the basis of grab sampling and epidemiology. However, the need for a new method has become highlighted as a variety of shortcomings of the use of indicator bacteria has appeared (Medema & Smeets, 2004).

2.2.1 Shortcomings of the use of indicator bacteria

To monitor the quality of drinking water, the occurrence of faecal indicators such as *Escherichia coli* in the end-product, has been measured. The use of indicator bacteria has generally resulted in drinking water of high quality but has over the years showed to have some shortcomings such as:

- Despite absence of indicator bacteria in test samples, waterborne disease outbreaks have occurred
- As the test sample only contributes a small fraction of the total volume and the microbiological test methods takes at least one day to produce a result, the end-product testing seems to be too little, too late
- The end-product testing doesn't provide safety in itself; it's only a receipt showing that all systems and measures are working normally
- The end-product testing approach is reactive rather than preventive (Medema & Smeets, 2004)

Taken together, the use of indicator bacteria only provides information about the product that is relevant for the specific time it was tested, and even then not for chlorine-resistant pathogens. Specifically, it does not provide information regarding previous and subsequent events between when relatively very small (100 mL) samples are collected (Ashbolt, 2006). Hence, from a public health point of view, the traditional end-of-pipe testing methods offer no or little protection from waterborne diseases (WHO, 2004).

2.2.2 The new risk based approach

To manage these shortcomings a new risk based approach has been proposed during the last decade. The new risk based approach consists of QMRA that aims to provide a scientific basis for risk management decisions as shown in Figure 2. (Medema & Smeets, 2004)

Exposure assessment comprises a description of risk scenarios as well as assessment of pathogen concentration throughout the treatment system as shown in Figure 3. 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)

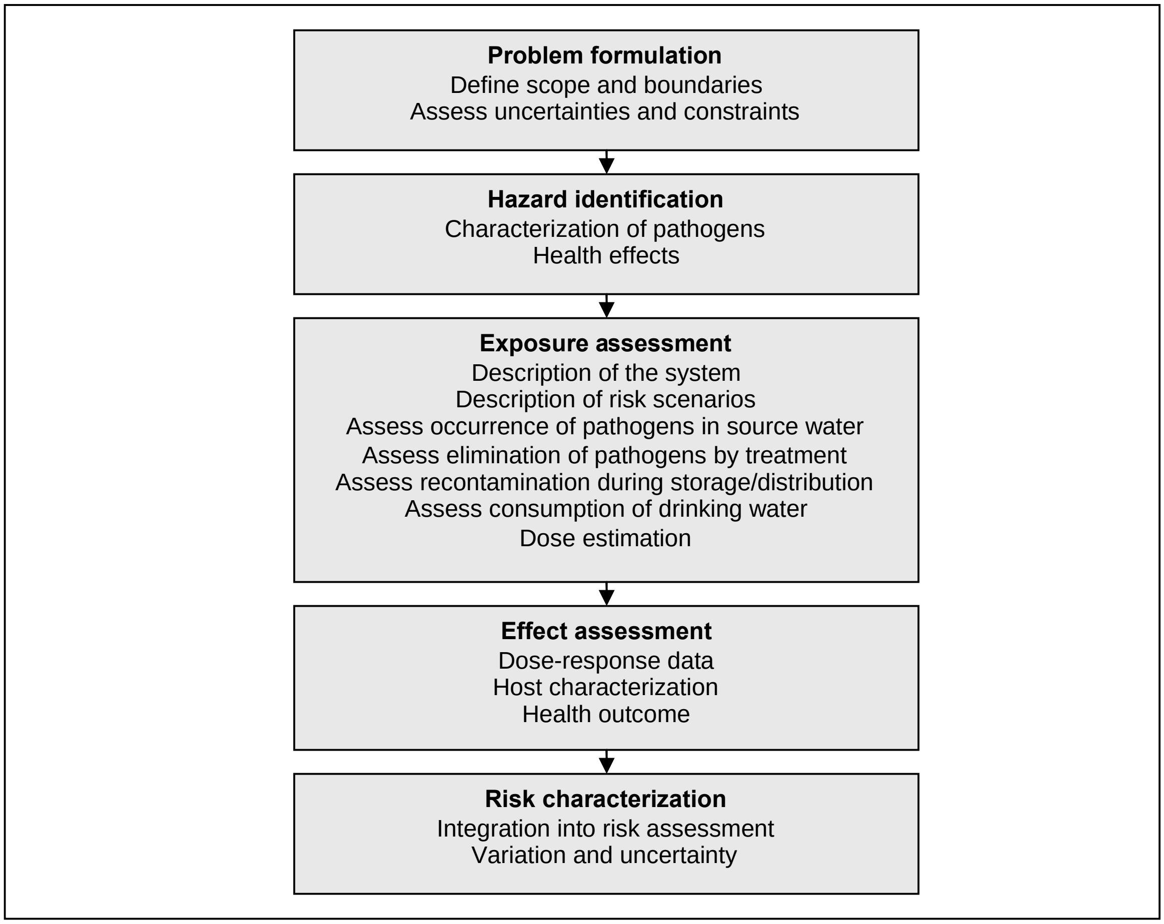

Figure 2. The steps in QMRA (Medema & Smeets, 2004)

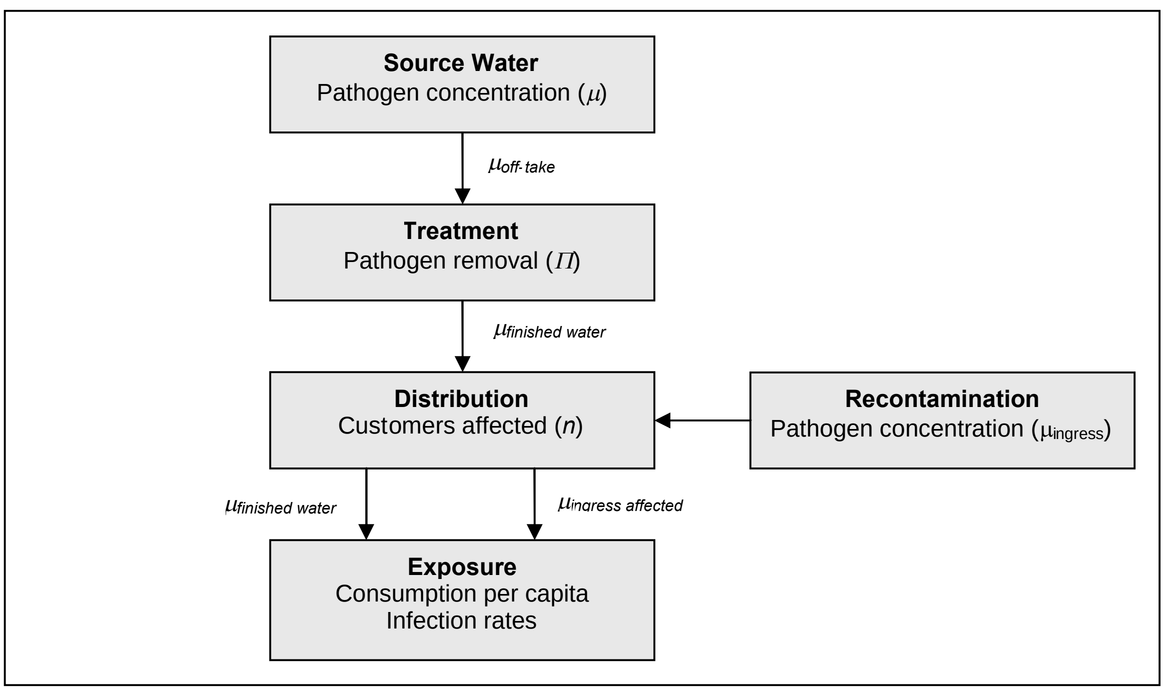

Figure 3. General QMRA framework (from Petterson et al., 2004)

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. This can be done in at least three ways as follows:

1. Pathogens – Measure of pathogen concentrations in inlet and outlet water is the most representative estimate of pathogen removal
2. Surrogates - Measure of pathogen surrogate concentrations in inlet and outlet water can contribute a useful estimate of pathogen removal
3. Process performance – Data such as SCADA data can be very useful to assess process performance and hence reveal hazardous events (Petterson *et al.,* 2004)

Given restrictions in time and money, option 1 is hard to pursue. Option 2 is feasible but is limited due to time demands and poor relationships between surrogates and pathogens. Although a measure of process performance can not always be directly translated to pathogen removal it can still prove to be a valuable source of information. For example, spikes in turbidity may indicate periods of poor performance and possibly be used as an indicator of hazardous event. (Roser, 2005)

The pathogen concentration in the water leaving the treatment plant for distribution is represented by $\mu_{finished\ water}$. The distribution may function as a potential entrance for pathogens due to contamination through leaking pipes etc. The entering pathogen concentration is represented by $\mu_{ingress}$. 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 affected or finished water is represented by *n*. By assessing the average water consumption per customer and combining the results with dose-response relationship (infection rates) pathogen exposure can be related to health outcomes. (Petterson *et al.,* 2004)

2.2.3 About Microrisk

Microrisk is a collaborative research project supported by the European Commission. The main objective of the project is to develop a method for QMRA of drinking water in EU member states. The overall outcome is a harmonised framework for risk assessment providing information for risk management. Microrisk and QMRA advocate the catchment to consumer approach as summarized in Figure 4. (The Microrisk consortium, 2005)

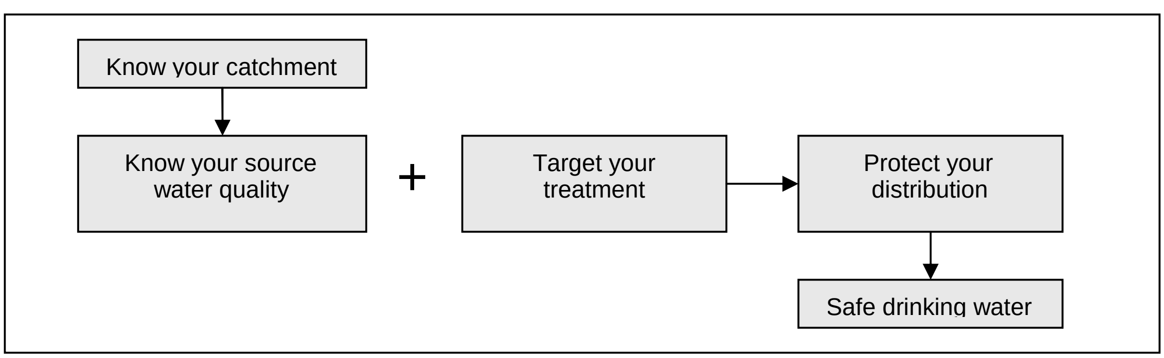

Figure 4. Catchment to consumer approach to risk management (The Microrisk consortium, 2005)

Partners included in Microrisk are: Kiwa Water Research (NL), Swedish Institute for Infectious Disease Control (SE), Veolia Water Partnership (UK), Veolia Environment (FR), Water Research Centre-NSF (UK), Institute of hygiene and public health at University of Bonn (DE), Suez Environment (FR), University of East Anglia (UK), TU Delft (NL), DVGW Technologiezentrum Wasser (DE), and UNSW - School of Civil and Environmental Engineering (AU). (The Microrisk consortium, 2005)

2.3 The Water Safety Plan (WSP) and Hazard Analysis and Critical Control Point (HACCP)

The main objective of the guidelines and the harmonised framework is to protect public health. WHO (2005) states that the most cost-effective and protective way to do this is by application of some form of risk management.

2.3.1 Water Safety Plan (WSP)

WHO (2005) propose the Water Safety Plan (WSP) to be the method to undertake risk management in the WHO harmonised framework. The WSP is a management system to facilitate management in the water treatment industry. The WSP, as shown in Figure 5, consists of three main components:

1. *System assessment* is made to determine if the water supply chain as a whole can deliver water that meets the quality targets
2. *Operational monitoring* is about control measures in the supply chain which are of particular importance in securing safe drinking water
3. *Management plans, documentation and communication* are about documentation of the system assessment, the monitoring and normal and corrective actions

2.3.2 Hazard Analysis and Critical Control Point (HACCP)

Hazard Analysis and Critical Control Point (HACCP) analysis is a management tool that has been used in the food industry for a long time. The rationale of HACCP is to control hazards at the time of manufacture rather than trying to detect problems by testing the end product. The method is based upon identification of each step within the process that can be crucial regarding to the safety and thereafter the taking of corrective action to reduce the risks.

HACCP is based on seven principles:

1. *Conduct hazard analysis* to identify hazards which may pose an unacceptable health risk to consumer
2. *Identify control measures* to define Critical Control Points (CCP) where control can be applied and a hazard can be prevented, eliminated or reduced
3. *Define operational limits* at the CCPs to define when the process is out of control
4. *Establish monitoring* to be able to identify out of control conditions
5. *Establish corrective actions and incident response* to prevent bad quality products from reaching the consumers
6. *Establish record keeping* to ensure effectiveness
7. *Validation and verification* to adapt to changing prerequisites or new needs (NACMCF, 1997)

HACCP has been proposed to be utilized in the water supply industry to reduce the risks to an acceptable level (WHO, 2005). HACCP has also been adapted into the WHO Water safety plans (Medema & Smeets, 2004) as shown in Figure 5.

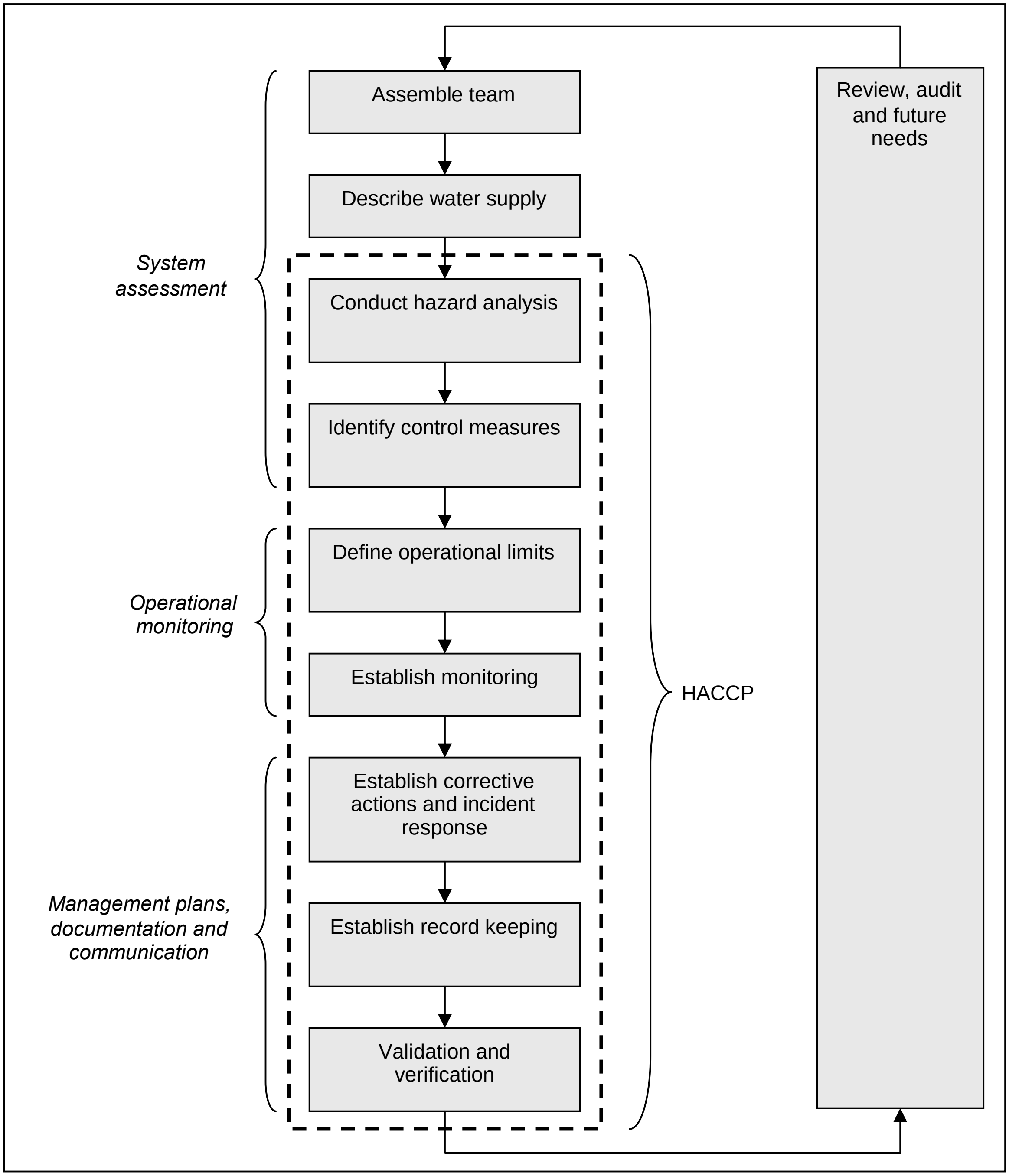

Figure 5. The components of the Water Safety Plan (WHO, 2005)

3 Water treatment

"Knowing your system" is a prerequisite for undertaking assessments of risks. This chapter gives a short introduction to water treatment processes and their ability to remove pathogens, i.e. reduce the risk. Also discussed is the important factor of variability which must be taken into account when assessing microbial risks. Various conceptions including general water treatment processes, pathogens, pathogen removal and treatment variability are introduced.

3.1 General water treatment processes

Water treatment is a complex process as several factors affect the final product. The aim for all water treatment processes is to produce water that is safe to drink at the most attractive overall cost. The choice of treatment design depends on:

- Source water quality
- Desired finish water quality
- Reliability of process equipment
- Operational requirements and personnel capabilities
- Flexibility in dealing with changing source water quality
- Available space for treatment facilities
- Waste disposal constraints
- Capital and operating costs
(Pontius, 1990)

The treatment design varies greatly. However, a generic system for conventional surface water treatment plants often includes:

- Coagulation
- Sedimentation
- Filtration
- Disinfection

3.1.1 Coagulation

Coagulation is about aggregation of small particles into larger ones that later on can be removed by sedimentation and/or filtration. Particles such as clay, silt, natural organic matter and constituents associated with these such as pathogens and metals can be removed. The coagulation process includes mixing, destabilization and flocculation. Mixing and destabilization is conducted in the rapid-mixing stage where treatment chemicals are added, hydrolyzed and dispersed to cause destabilization. Alum and iron (III) salts are often used as the treatment chemical. In the flocculation step, small particle aggregate to larger particles through interparticle collisions performed in a basin divided into three or more compartments. The performance of the coagulation is dependent on particle suspension, chemical dose, pH, temperature, ionic strength, and reaction time. (Pontius, 1990)

3.1.2 Sedimentation

Sedimentation is a separation process where gravity causes solid particles to sink to the bottom of the water column. The accumulated solid on the bottom is then removed on a regular basis. Sedimentation is often used in systems following coagulation.
The efficiency of sedimentation is dependent on prevailing hydraulics and flow. If short circuiting and turbulence are avoided the process runs optimally. Poor inlet distribution and bad design of sedimentation basins counteract good performance. (Pontius, 1990)

3.1.3 Filtration

Filtration is the most common way to remove suspended particle matter and pathogens associated with these particles. The process can either be slow or fast depending on the filter media. Filters often consist of granular media such as sand, coal, or granular activated carbon (GAC). Each filter runs in a filter cycle (see Chapter 3.4.2). The efficiency of the filter is dependent on filter design, granular media type, pore size, holding capacity, head loss characteristics, filtrate quality, and backwash requirements. (Pontius, 1990)

3.1.4 Disinfection

Disinfection, such as chlorination, constitutes one of multiple barriers to assure the production of safe drinking water. Chlorine is sometimes also added to restrict microbial growth within the water treatment plant such as in filters, basins and channels. The performance of chlorination is dependent on many factors including temperature, pH, water quality and contact time. Chlorine impacts on microbial concentrations as the substance can enter a lot of reactions within a cell causing inactivation. Chlorine and chlorine dioxide are very potent disinfectants but there are also a lot of problems associated with the two. High concentrations of chlorine and its by-products have been found to cause harmful effects in 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)

3.2 Pathogens

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 that is contaminated with human and animal excreta is the most significant route of exposure. The impact on public health is dependent on the pathogens health significance, their infectivity and the population exposed. The most common pathogens, their significance for health and their known health effects are summarized in Table 1. (WHO, 2004)

The pathogens in drinking water are a highly diverse group. Bacteria are single-celled micro-organisms. 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. Viruses are parasitic and infectious microbes composed of protein and nucleic acids. Viruses need to be within a living cell to reproduce. Viruses are typically 0.004 to 0.1 micrometers in diameter. Protozoa are micro-organisms that can exist as single cells or in colonies. Some of the strains are able to produce cysts. Cysts are small reproductive bodies that are capable of protecting the organism under unfavourable conditions. The typical size of protozoa is 2 to 25 micrometers. Algae range from single-celled organisms to multi-cellular organisms. They typically range in size from 5 to 100 micrometers. With the exception of toxic species, algae are generally not a direct threat to public health. Concerns are generally due to their ability to create large amounts of organic matter which can have an impact on turbidity, taste and colour and hence affect the treatment efficiency or esthetical aspects of the water. (USEPA, 1999)

Table 1. Pathogens and their possible health effects (Nadebaum et al., 2004; WHO, 2004)

Type	Pathogen	Health significance	Possible health effect
Bacteria	*Campylobacter jejuni*	High	Acute gastroenteritis
	Escherichia coli	High	Some strains causing gastroenteritis, diarrhoea and sometimes death
	Legionella	High	Legionellosis, Pontiac fever
	Non-tuberculous mycobacteria	Low	
	Pseudomonas aeruginosa	Moderate	Rashes and ear infections, infection of wounds
	Salmonellae typhi	High	Gastroenteritis with diarrhoea or enteric fever
	Other salmonellae	High	
	Shigella spp	High	Dysentery
	Vibrio cholerae	High	Cholera
	Yersinia enterocolotica	High	Pathogenic strains cause acute gastroenteritis
Viruses	Adenoviruses	High	Pharyngitis, conjunctivitis, gastroenteritis
	Enteroviruses	High	Often symptomless, but 0.1% to 1% of cases can cause sore throats, rashes, aseptic meningitis, gastroenteritis, cardiac symptoms, and conjunctivitis.
	Hepatitis viruses	High	Hepatitis A may cause mild symptoms or more severe illness and rarely death. Hepatitis E are generally mild except in women in the late stages of pregnancy, where risk of death is 20%.
	Norwalk viruses	High	Rapid epidemics of gastroenteritis and sometimes also vomiting, fever, and chill.
	Rotaviruses	High	Severe gastroenteritis in children and elderly. Fever and vomiting are other symptoms. Occasionally fatal.
Protozoa	*Cryptosporidium parvum*	High	Diarrhoea
	Giardia intestinalis	High	Diarrhoea and reduced absorption of nutrients
Toxic algae	Cyanobacteria		Pathogenic species release toxins that can harm liver cells or nerve cells

3.3 Pathogen removal processes

Well operated treatment processes normally constitute effective barriers preventing pathogens from reaching the consumers. However, there are a lot of factors that affect the performance.

3.3.1 The Multiple Barrier Concept

High quality drinking water is established upon the multiple barrier concept. A barrier can constitute a physical obstacle, such as a filter, but can also be a management issue, such as information or education. The multiple barrier concept is based upon the idea that not one, but several, such barriers summarized will constitute a good protection. If pathogens manage to pass through the first barrier, the following barriers should be able to minimize the presence of it. The exact configuration differs but the barriers can be classified as by Fox (2003):

1. Source water protection
2. Water treatment processes
3. Disinfection and well maintained distribution
4. Education

Source water protection refers to choosing the best available source water and the protection of it. Water treatment facilities refer to all water treatment techniques and the proper management of them. Disinfection is the last physical barrier where inactivation of pathogens is possible. This step doesn't only include the disinfection provided at the water treatment plant but also maintenance of a disinfection residual throughout the distribution system and proper maintenance of pipes etc. to avoid contamination from earth. Education of water treatment staff and management as well as water consumers has proven to be a very effective barrier. Without well educated treatment staff and management the process will not be optimal and the first three barriers will be weakened. (Fox, 2003)

Livsmedelsverket (2004) has another view of the barrier concept where the following treatment steps counts as working barriers:

1. Artificial infiltration of surface water
2. Chemical precipitation with following filtration
3. Slow filtration
4. Disinfection
5. Membrane filtration

The barrier effect for treatment facilities is detaching and decanting/sedimentation or inactivation. For example, chemical precipitation with following filtration relies on detaching whereas disinfection relies on inactivation. The barrier concept works optimally if both principles are used at the same time. The total amount of barriers is dependent on the quality of the surface water as well as of required final product, that is, the desired quality of the drinking water. (Livsmedelsverket, 2004)

3.3.2 Removal by treatment processes

The removal of pathogens is commonly denoted by ^{10}log-removal where 1 ^{10}log-removal correspond to a removal of 90 % of the organisms, 2 log to 99 %, 3 log to 99.9 % etc.

The basic principle for removal of pathogens in conventional water treatment is:

1. Coagulation and sedimentation
2. Filtration
3. Disinfection

Coagulation is a critical treatment process for effective removal of pathogens. Together with sedimentation this step can contribute an approximate value of 1-2 ^{10}log-removal of bacteria, viruses and protozoa (Hijnen *et al.,* 2005). Lime softening is used before coagulation to elevate pH for optimal conditions. Lime softening can also provide good pathogen removal through a combination of inactivation by partly high pH (e.g. pH 10-11) and partly removal by sedimentation (LeChevallier & Au, 2004).

Filtration removes pathogens through a combination of physical and chemical properties. The filtration process is strongly dependent on the optimal clarification process. A total of 1-4 ^{10}log-removal of bacteria, viruses and protozoa can be achieved (Hijnen *et al.,* 2005). However, if the clarification does not work as intended the filtration will not be an effective barrier against pathogens (LeChevallier & Au, 2004).

Disinfection with chlorine will inactivate a variety of pathogens. This process is dependent on disinfectant concentration, contact time, temperature and pH. Disinfection provides an approximate 2 ^{10}log-removal of bacteria; however, some bacteria such as *Clostridium* are highly resistant to chlorine and will experience less than a 2 ^{10}log-removal. Viruses are generally more resistant to chlorine than bacteria. Protozoa such as *Giardia* and *Cryptosporidium* are highly resistant to disinfection with chlorine. However, chlorine dioxide has proven to be a potent disinfectant for *Giardia.* (LeChevallier & Au, 2004)

3.3.3 Relationship between treatment processes

The multiple barrier concept is based on the premise that if the first barrier fails this should be compensated by the next barrier. In water treatment supply this means that if one treatment step works suboptimal or malfunctions this should be compensated by application of the next treatment step. However, in water treatment supply this is not always the case as treatment processes are related to each other in that the performance of one treatment step can affect the efficiency of the next step. For example:

- Pre-oxidation affects filtration. Pre-oxidation affects the surface properties of particles and microbes and make them easier to reduce later on in the filtration (Au *et al*., 2002).
- Clarification affects sedimentation. If the clarification doesn't remove suspended solids these are likely to weaken the performance of the filter (LeChevallier & Au, 2004)
- Filtration affects disinfection. If the filtration fails in its removal of particles or turbidity this can reduce the performance of disinfection processes (LeChevallier & Au, 2004).

3.4 Variability

Drinking water treatment is a dynamic process as the raw water quality as well as the treatment efficiency is variable. Some variability is normal as well as expected. However, too much variation can, under unfavourable conditions, reduce the systems overall capacity to deliver safe drinking-water.

3.4.1 Raw water variability

Seasonal and local situations can affect the raw water quality in many ways. The quality can be affected by both natural and human factors. Natural factors include climate such as heavy rainfall or snow melt followed by surface runoff or wildlife excreta from birds. Human factors include point sources such as discharge of waste water and non-point sources such as urban runoff. Raw water changes can degrade the performance of the water treatment processes or be a health risk in themselves as it might contain pathogens (LeChevallier & Au, 2004). Hence, changes in raw water must be taken into account for optimal performance of a water treatment plant.

3.4.2 Treatment efficiency variability

The treatment efficiency for removal of pathogens is likely to vary between plants and treatment processes. The filter cycle is a good example of the dynamics within the treatment processes. A filter run constitutes three periods: the ripening period, the optimal operating period and the breakthrough. After a filter has been backwashed it performs poorly during the ripening period. In the optimal period the filter achieves a stable level of performance. The optimal period is followed by degradation and eventually a breakthrough. (LeChevallier & Au, 2004)

The impact of different performance levels could ideally be managed by the use of several filters. Filters run in different stage of the cycle will reduce the effect of temporary bad performance in one filter (LeChevallier & Au, 2004). Still, according to Bergstedt (2005) this only applies if the performance difference is small; for example, if one filter out of sixteen has a 2 log reduction in performance and this is divided on all sixteen filters, it still provides a great increase in risk. Under unfavourable conditions, the net outcome can be that the treatment efficiency is too low. Drinking-water guidelines can be used to state whether the process is kept within acceptable limits (LeChevallier & Au, 2004).

3.4.3 Implications for monitoring

Because of the dynamics within the treatment processes, monitoring must include techniques that accounts for variability (LeChevallier & Au, 2004). This can be a problem, especially if few measurements are performed (Frey *et al.*, 1998). Another problem is that direct measurements seldom can be used. Instead, indirect measurements such as turbidity or particle count values will act as a measure of treatment performance. Indirect measurement are measurements that act as a surrogate for a direct measurement when such is not at hand. This adds extra uncertainty as one can not be sure if the observed treatment performance and variability reflects the actual performance (LeChevallier & Au, 2004).

3.4.4 Implications for microbial risk

LeChevallier & Au (2004) propose that health effects associated with pathogens tend to be due to short-term rather than long-term exposure. This fact highlights the importance of maintaining reliable treatment performance for minimizing microbial risk. Findings in the research programme Microrisk showed that short term event conditions contribute to a greater increase in risk than the increase in risk arising from normal operation and that disinfection malfunction is the most influential factor (Roser, 2005). Further, WHO (2004) states:

"Microbial water quality may vary rapidly and widely. Short-term peaks in pathogen concentration may increase disease risks considerably and may also trigger outbreaks of waterborne disease. Results of water quality testing for microbes are not normally available in time to inform management action and prevent the supply of unsafe water."

Westrell *et al* (2003) state that it is clear that it is under normal conditions and not during failures, that most infectious matter bypasses the treatment. Further, Westrell *et al* (2003) also state that the variation in raw water concentrations of pathogens is the most influential factor affecting the risk but that the main risk incidents in water treatment are associated with sub-optimal particle removal or disinfection malfunction. Taken together, variability affects the outcome of the risk assessment. Managing small undetected events can be an efficient way of reducing health risks.

4 On-line monitoring

On-line monitoring systems generating high resolution data such as SCADA systems are, in theory, ideal sources of data for quantitative risk assessments and hence, a proposed way to improve the risk management process. However, a lot of problems are associated with the current use of SCADA systems and their connection to risk management. This chapter provides an introduction to what SCADA is, its current use in water treatment supply, the relation between SCADA and microbial risk, and its general values and shortcomings.

4.1 What is SCADA data and how is it used?

A SCADA system is a system that is used to:

1. Acquire data from a process
2. Control the process

The meaning of the term SCADA differs depending on the industry where it is utilized. In the water community with systems scattered over large areas the SCADA systems are usually used for acquisition of data. But the system could also be set up as a process control system enabling the operator to control the plant from a computer in a control room. SCADA systems encompass sensors or IEDs (Intelligent Electronic Devices), PLC (Programmable Logic Control) or DCS (Distributed Control Systems), a field bus and a computer. SCADA is about collecting information, transferring the information back to the central site, carrying out any necessary analysis and finally displaying the information for the operator. (Bailey & Wright, 2003)

The SCADA systems used in water treatment plants enable monitoring of a wide range of parameters such as turbidity, particle size, particle count, temperature, flow, pH, conductivity, redox, ozone and oxygen. These systems are used world wide, not just in water treatment systems, but in all process industry. For example, Scott *et al* (1999) estimate that there are more than 170 000 on-line instruments in the UK in the water and waste water treatment industry.

4.2 What are the values and the limitations with SCADA data?

Scott *et al* (1999) reason that as the society in increasing extent tends to put the risks in focus it is likely that regulators and public opinion will demand better quality measurements to prevent or manage the risks. Further, Scott *et al* (1999) states:

"The current reliance on sampling and laboratory analysis exposes companies to the risk of undetected incidents; suggesting the need for continuous measurement so as to demonstrate diligence."

One of the problems associated with the current way of sampling and laboratory analysis is that of exposure for risks of undetected hazardous events, and this problem highlights the need for continuous measurement that can deal with such events (Scott *et al.,* 1999). Continuous monitoring is a proposed strategy to improve risk management (Cutler, 1997).

Bailey & Wright (2003) point out some advantages with SCADA:

- The computer can record and store large amount of data
- The data can be displayed the way the user requires
- The data can be viewed from anywhere
- A lot of sensors can be connected to the system

Within the water supply area it seems to be a general opinion that on-line monitoring is vital in controlling risks. However, there also seems to be a lack of confidence in on-line monitoring. The prevailing culture seems to be "fit and forget" sooner than "fit for purpose". For example, operational costs could be reduced by one third by more effective use of on-line measurement. Furthermore, at least 20 % of the 170 000 on line instruments installed in the UK water and waste water industry serves no useful purpose or isn't installed or operated correctly. (Scott *et al.,* 1999)

Scott *et al* (1999) lists various problems with the use of SCADA data:

- No standards
- Lack of communication
- Indifference of the contractor to the benefits
- Acceptance of error prone and out of date information
- On-line instrumentation is very wide and rapidly changing, and hence hard to survey
- Technologists put far too little effort into informing management about the business benefits

Bailey & Wright (2003) points out some further disadvantages:

- The system is more complicated than sensor to panel
- Different operating skills are required
- The operator can not see beyond the sensors

4.3 Noise

Noise is an important factor to consider when undertaking on-line monitoring. Bailey & Wright (2003) define noise as:

"Noise is the random generated undesired signal that corrupts or interferes with the original signal."

The noise can be generated in the system itself or from outside sources. SCADA systems use low voltages which make them inherently susceptible to noise (Bailey & Wright, 2003). As the noise is random in nature and hence, unpredictable, it will add additional uncertainty to the measures taken.

4.4 Conceptual relationship between SCADA data and microbial risk

How can a barrier effect be measured? Direct analysis of pathogens is in most cases too labour and time demanding to be of value as a control of the performance. In addition, concentrations of micro-organisms are usually too low to constitute a valuable measurement for quantitative assessments. Hence, it is not possible to measure detaching or inactivation by grab sampling on each water treatment plant. To be able to control the barrier efficiency in reducing pathogens indirect methods must be used instead. Some SCADA parameters may function as surrogate measurements for microbial activity and can easily be monitored on a regular basis. Even though most SCADA parameters do not provide direct information about the presence of pathogens they can still provide information on the process efficiency, and hence, act as an indirect measurement of pathogen removal. (Roser, 2005)

The preventive measures must not only be implemented but also monitored in an efficient way. To ensure processes and activities run as intended they must be continually monitored. The aim with monitoring is to demonstrate that the hazards are under control. For preventive measures which are important for preventing hazards, on-line monitoring is preferable (Nadebaum *et al.*, 2004).

4.4.1 Turbidity

Turbidity is a measurement of light scattering and absorbance by particles. Hence, turbidity is a measure of the relative clarity of a liquid.

The particles can be divided into three main groups:

- Inorganic particles such as silt or minerals
- Organic particles such as decomposed natural compounds as well as agricultural and industrial compounds
- Biotic material such as bacteria, viruses, protozoa, and algae
  (USEPA, 1999)

Turbidity is often caused by the following sources:

- Waste discharge
- Runoff from watershed
- Algae blooms
- Humic acids resulting from decay of plants
- High iron concentrations leading to a rust-red coloration
- Air bubbles and particles or sludge sheets from the treatment
  (USEPA, 1999)

Although turbidity itself is not a health risk it can be a warning of microbiological presence in the water as:

1. Suspended particles can carry potentially pathogenic micro-organisms
2. High turbidity can indicate a failure of particle removal processes
3. Turbidity can shield micro-organisms from disinfection

USEPA (1999) states that there is significant evidence to suggest that controlling turbidity is a competent safeguard against pathogens in drinking water, and that numerous studies show a strong relationship between removal of turbidity and removal of protozoa. For example, Patania *et al* (1995) showed that a filter effluent turbidity of less than 0.1 NTU resulted in effective cyst removal by up to 1.0 log greater than when filter effluent turbidity was within the range 0.1-0.3 NTU. Livsmedelsverket (2004) claims that measurements of turbidity in the treatment process and on the outgoing drinking water are important to assure the microbiological barriers work as intended. A short elevation of turbidity values may indicate an increased risk for waterborne disease. Even though elevated values are generally considered being events, it can also be the other way around. For example, low turbidity values indicate possible failure in the process of coagulation of dissolved humic acids (Bergstedt, 2005). Hence, the statement that elevated turbidity value is an event is true but still a simplification.

Meters should be designed to detect changes of 0.1 FNU or less. The measurements should also be continuous. Ideally, the turbidity should be measured at several locations during the treatment process. For example, if the turbidity is measured before and after each filter it will provide the ability of indicating a single bad filter performance. This ability might be lost if the measurement is done on the assembly filtrate. One problem with measuring the turbidity is that it doesn't say what sort of particles that pass the treatment. Even when measured turbidity values are low, a range of pathogenic micro-organism may be present. (Livsmedelsverket, 2004)

4.4.2 Chlorine residual

The term chlorine residual, or as it is also called, total available chlorine, refers to the sum of free-chlorine compounds and reactive chloramines. Even though measurement of available chlorine is not fully sufficient to characterize disinfection performance as the efficiency of the various combined chlorine forms as disinfectants differs, it is a parameter that is feasible to measure with a SCADA system (Pontius, 1990). The chlorine residual level must be set in light of given preconditions and on the basis of prevailing requirements. Deviation in, or absence of, chlorine residual can contribute to a breakthrough of micro-organisms (Roser, 2005). Hence, monitoring and controlling the chlorine residual is important since lack of disinfectants is equal to the absence of an important barrier.

4.4.3 pH

pH is a measurement of the acidity of a solution. pH is defined as the negative logarithm of the concentration of hydrogen ions in a solution. pH is likely to vary in different source water and it will also be changed during the treatment process; for example, liming and alum dosing will change the pH. Very acidic or basic water can constitute a health risk in itself. Even though there have been accidents with high pH in drinking water due to too high dosing of lime this is not a common problem (Bergstedt, 2005). Instead, pH could be useful as an indirect measurement if processes such as the coagulation work properly.

Before coagulation, lime or caustic soda is added to provide necessary alkalinity and to keep the pH conditions, after addition of alum, in the range where optimum coagulation occurs (Pontius, 1990). As the alum dosing has an acidic effect, measurement of the pH can be a way of telling if the alum dosing was correct. This is of importance since the alum dosing is of significance for removal of micro-organisms. Dugan *et al.* (2001) showed that *Cryptosporidium*, aerobic spores and particles were removed less efficient during periods with suboptimal coagulant dosing. Ongerth and Pecoraro (1995) showed that using very low turbidity source waters (0.35-0.58 NTU), 3 log removal of *Cryptosporidium oocysts* was obtained for optimal coagulation and 1.3-1.5 log removal for suboptimal coagulation.

As well as affecting the coagulation process, pH has a great influence on a range of other water treatment processes:

- High pH constitutes an effective barrier against viruses; Rao *et al.* (1988) showed that at pH 11, all viruses were efficiently removed
- pH has a great effect on chlorine disinfection; free chlorine at low pH is more potent as disinfectant than at high pH (Pontius, 1990)
- pH should be kept within given limits to avoid corrosion or scaling of pipes (Nadebaum *et al.,* 2004)

4.5 On-line measurement and HACCP

In controlling the risks on-line measurement has a close connection to HACCP and Critical Limits at Critical Control Points. Historically, the setting of critical limits has involved setting a target for performance such as a bacterial indicator. However, an on-line measurement could be confirmation showing that the critical limit is not exceeded. It is proposed that the critical limits should be based on the combination of rates of failures and assessments of how long a suboptimal performance can be tolerated before risk becomes unacceptable (Roser *et al.,* 2005). SCADA data analysis can, in theory, yield rates of failures and QMRA can yield the acceptable time of period with suboptimal conditions.

5 Time series analysis

A time series is basically a set of data points collected at regular time intervals. Time series analysis is a methodology to understand time series such as those generated by SCADA instruments. To identify and quantify hazardous events in SCADA sets, time series analysis can prove to be a valuable methodology. This chapter describes two common methods to undertake time series analysis; by control charting and by change point analysis.

Improved time series analysis seems to offer a range of benefits for risk management. Probabilistic Risk Analysis (PRA) is a methodology where historical data is extrapolated to derive an overall probability for the occurrence of a hazard. Such an approach could be used to make forecasts or predictions about coming events. The last part of this chapter reviews the connection between time series analysis, PRA and monitoring.

5.1 Control Charting

Control charting is a well proven industry quality control method. Since quality control is an economic issue in that way it provides techniques for increased profitability it also has a long history. However, statistical quality control is a comparatively new concept. It was not until the 1920s when Dr. Walter A. Shewhart proposed a general model for control charts that statistical theory became effectively applied to quality control (NIST/SEMATECH, 2005). Nowadays, control charts are the preferred method when data is collected at a regular basis (Taylor, 2000). Control charting is widely used in the industry to monitor process performance and to identify instability and unusual circumstances. However, there is still much controversy as to which statistical methods that are best suited interpreting the data collected (Devore, 2000).

5.1.1 Shewharts General Model for Control Charts

Typically, a control chart plots sample quality versus the sample number or versus time as shown in Figure 6. In this case, the sample quality is normally distributed. The chart contains a center line that represents the mean or the target value for the process. The upper control limit (*UCL*) and the lower control limit (*LCL*) demarcates the target range for the process. *UCL* and *LCL* can be based on the variability of the samples but can also constitute a given limit that the process needs to fulfil.

Back in the 1920's, Dr. Walter A. Shewhart proposed a general model for control charts as follows. Let w be a sample statistic with mean μ_w and standard deviation σ_w. Then the *UCL*, *Center line* and *LCL* are:

$$\left.\begin{aligned} UCL &= \mu_w + k\sigma_w \\ Center\ line &= \mu_w \\ LCL &= \mu_w + k\sigma_w \end{aligned}\right\} \qquad \textit{Equation 1}$$

The distance of control limits from the *Center line* is labelled k and is expressed in terms of standard deviation units.

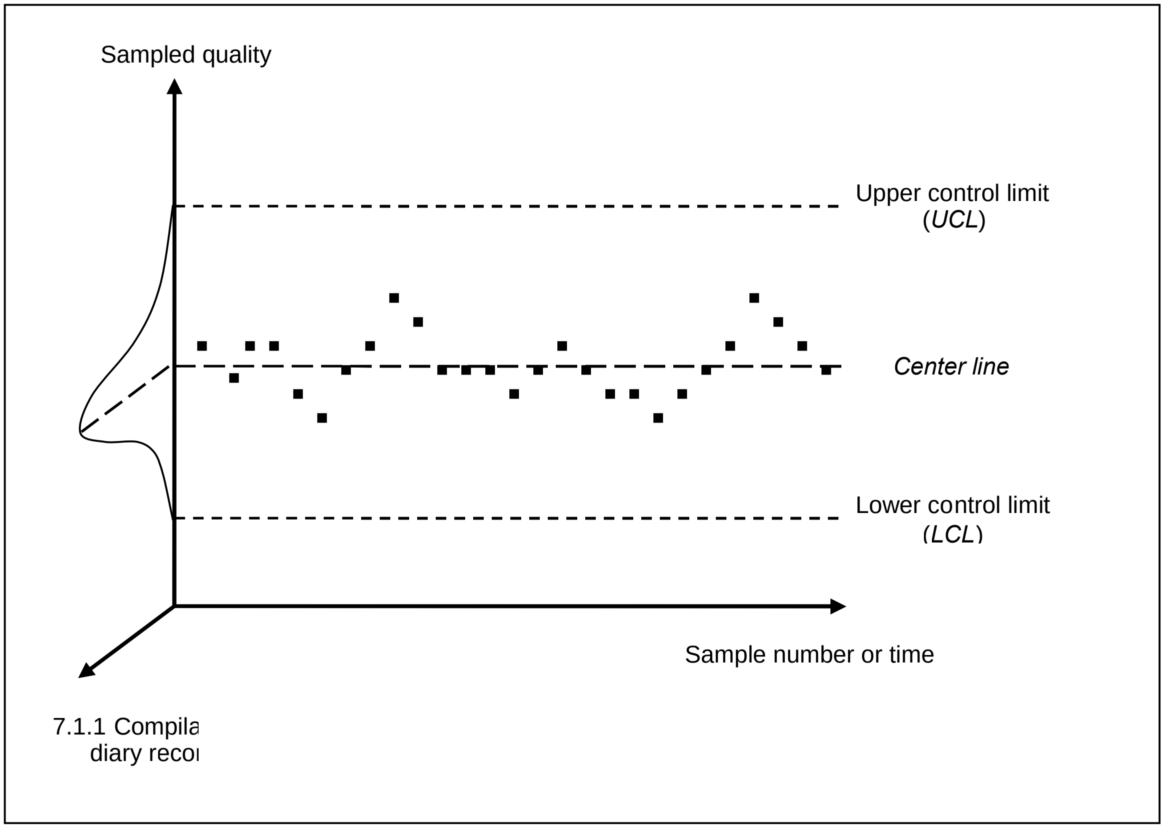

Figure 6. Chart demonstrating basis of control chart

The UCL and LCL can be set arbitrarily, but most commonly represent the .001 probability limits. This is known as the plus or minus 3-sigma limit, which is used in industry world wide. The 3-sigma limit corresponds to the .001 probability in the way that 3σ equals 0.00135. This will mean that the probability for a point falling above the upper or below the lower limit is one out of a thousand. Hence, the probability for a point to deviate from the target range is in this case two out of a thousand. (NIST/SEMATECH, 2005)

If a point falls outside the target range the process is assumed to be out of control and studies would then be pursued to find the assignable cause for deviation. The position of the limits will determine the risk of undertaking such a study when there in reality is no assignable cause for variation (NIST/SEMATECH, 2005), that is correct limits allow the user to separate probable noise and inherent variability from potential hazardous events. Hence, the positions of UCL and LCL are questions about tolerable risk and risk management.

Even though all points fall within the target range this doesn't necessarily mean that the process is under control. If the points are non-randomly distributed this can imply that the process is not in control. There are statistical methods to detect non-random patterns. To be sure that the process is under control, all samples must be between control limits and they must also form a random pattern. (NIST/SEMATECH, 2005)

Shewhart control charting is based on the idea that the underlying data is normally distributed, and this is also often the case in manufacturing industry. However, Lake *et al* (2002) showed that turbidity data sets is not normally distributed, rather being skewed positively (Agutter *et al.*, 2001) with a longer tail to the higher values than the lower. To cope with this fact, percentile charts has been proposed as a better basis for the setting of proper alarms for process streams at water treatment plants (Lake *et al.,* 2002).

5.2 Change Point Analysis

Change point analysis is a newer tool for interpreting time series. The analysis aims to determine whether a change has taken place or not. There are numerous ways of undertaking change point analysis and they all have different benefits and shortcomings.

The strength of change point analysis is that it is capable of detecting slight changes missed by control charts and it better characterizes the detected changes. When dealing with large sets of data, change point analysis is also to prefer to control charting. However, the change point analysis should not be considered as a replacement for control charting, but rather a complement (Taylor, 2000). A common way of undertaking change point analysis is by Cumulative Sum Control Charting (CUSUM).

5.2.1 CUSUM

There are a many different CUSUM procedures. However, for each procedure the underlying theory is the same. The simplest CUSUM charts are constructed from a cumulative sum based on the data. The CUSUM chart is created by calculating the cumulative sum, S_i, as below.

$$S_i = S_{i-1} + (X_i - X_{mean}) \qquad \text{Equation 2}$$

where i is the number of the data point, X_i the data point and X_{mean} the arithmetic mean of the data points. S_0 equals 0. (Taylor, 2000)

This is exemplified in Figure 7. The time series consists of 24 data points as shown in Table 2. The cumulative sums are then calculated as follows.

$$X_{mean} = \Sigma(X_1, \ldots, X_{24}) / 24$$

$$S_0 = 0$$

$$S_i = S_{i-1} + (X_i - X_{mean})$$

Table 2. Time series data and corresponding CUSUM (S_i)

I	X_i	S_i
0		0
1	10.7	-0.7
2	13.0	1.0
…		
24	9	0

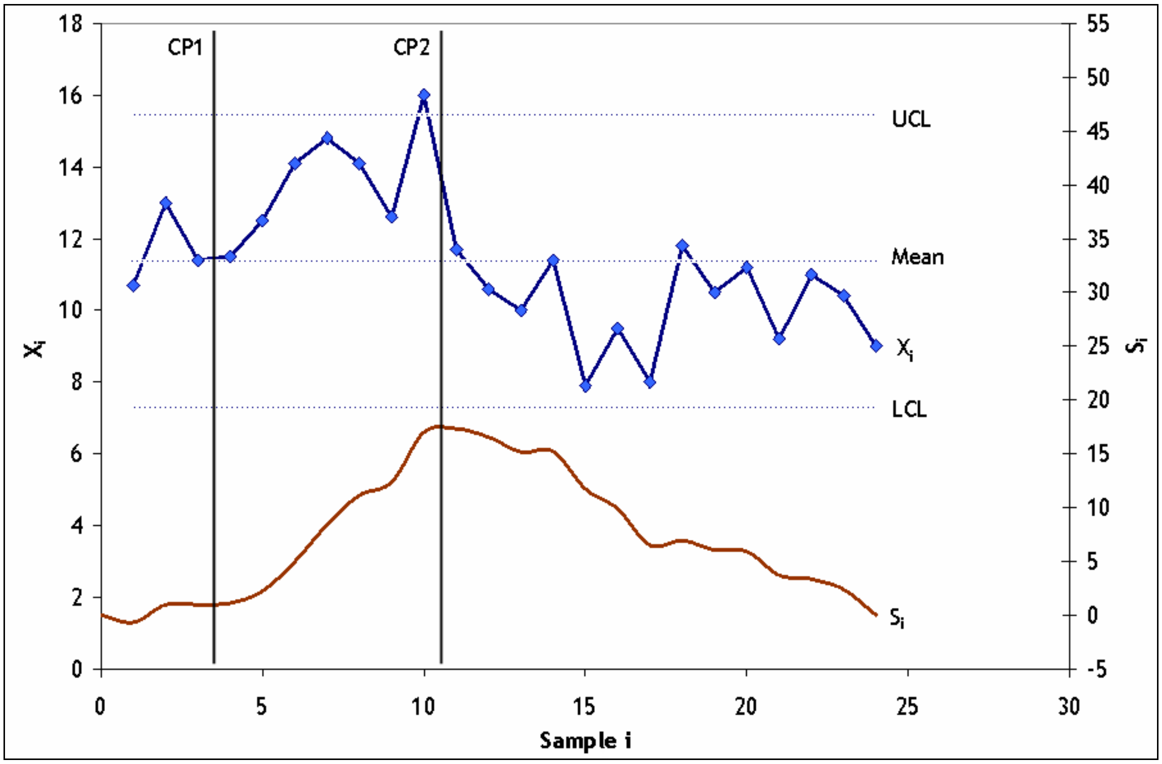

Figure 7. Plot of data and corresponding CUSUM (CP1 = Change Point 1, CP2 = Change Point 2, UCL = Upper Control Limit, Mean = Arithmetic mean of samples, LCL = Lower Control Limit, X_i *= Data point,* S_i *= CUSUM, i = number of data point)*

A CUSUM chart is interpreted as follows:

- An upward slope indicates a period with values above arithmetic mean
- A downward slope indicates a period with values below arithmetic mean
- A sudden change in direction indicates a change point
- If the chart follows a straight path this indicates a period with values at arithmetic mean

At i = 10 the sample exceeds the *UCL*, indicating that the process is out of control. This change would have been picked up by control charting. However, the sudden change in the CUSUM chart indicates that change points took place at i = 3.5 and i = 10.5 and hence, that the underlying cause to the exceeded target value took place at around i = 3.5. In this way, the CUSUM chart work as a compliment to control charting in that way it can provide valuable information on underlying causes to deviation. (Taylor, 2000)

The CUSUM technique has been examined within Vivendi Water Partnership (Agutter *et al.,* 2001) and in the UK industry (Hall *et al.,* 2000; Wetherill & O'Neill, 2000). The studies show that there are drawbacks to CUSUM as there are different approaches to determine the "normal" value. The "normal" value refers to X_{mean} in *Equation 2*. This value can constitute a historical value such as the annual arithmetic mean or the arithmetic mean from the latest hour. It can also constitute a set target value for the process. Depending on what "normal" value is used, it considerably affects the results. Furthermore, the studies show that CUSUM analysis is likely to increase the workload for the plant operator which could increase the risk that less care is taken to traditional analysis.

5.3 The connection to Probabilistic Risk Analysis

Probabilistic Risk Analysis (PRA) is a methodology that aims to derive an overall probability for the occurrence of a hazard. The starting point for the analysis is a set of elementary events whose probabilities are known from historical data, test data or expert opinion. The hazard is then expressed as a logical function from the sets of the elementary events.

The process of PRA has been criticised because of its statistical rigour and the problems associated with future predictability. The statistical concepts of evenly distributed events, different statistical techniques or sampling error are all contributing to uncertainty. However, by far the most important source of uncertainty lies in assuming that future events will have a similar probabilistic behaviour. (Cutler, 1997)

To understand how historical data can be extrapolated to the future one must distinguish between common and special causes of variation. Common causes of variation are part of a stable system and are predictable in frequency and severity. On the other hand, special causes of variation are outside the system and are intrinsically unpredictable in frequency and severity (Cutler, 1997). Shewhart (1931) deemed that “stable and predictable processes are not state of nature and are only achieved after extensive work on the process to eliminate special causes”. Furthermore, Deming (1975) observed that special causes of variation (failure) reduce the ability to make predictions about future behaviour. A stable and predictable process is a fundamental premise to make useful predictions by PRA. However, to be able to say that the process is stable, it must be monitored to identify and eliminate special causes of variation. This also applies when special causes of variation are removed as to assure that they do not reappear.

Shewhart (1931) proposed the control chart to identify special cause of variation. Cutler (1997) suggests that construction of a control chart of hazardous events is of limited value as they only monitor exactly what is experienced by the customer and only once the customer also has identified them. Such measurements, for example the time between hazardous events are called results measures (R-measures). In contrast to R-measures, process measures (P-measures) can be used. Process measures are factors that can contribute information about safety. These have previously been referred to as indirect measurements. By studying P-measures one could in theory be able to predict when a hazard is at hand, e.g. the P-measures could be used to provide advanced warning of the unexpected. For example, relevant P-measures for a pump might include:

- Frequency of single pump faults
- Noise, vibration and temperature measured at pump
- Frequency of pump overhaul
- Manufacturing data from pump supplier
- Pump condition on failure

Applied to water treatment systems, the R-measure could be the time between hazardous events whereas the P-measure could be the value for turbidity, pH or chlorine residual. Any of these measurement can help to forecast a deviation in pump deterioration and hence a hazardous event. Perrow (1984) states that "concentration on R-measures frequently neglects evidence of emergent and unanticipated behaviour in complicated systems and that P-measure are needed to give advanced warning of the unexpected".

Diligent monitoring might at a first glance seem unnecessary and not cost effective. However, Cutler (1997) considers that the process of measurement and control charting improves performance and reduces operating costs as the collection of data captures new knowledge about the system. This learning can later be used in design and risk assessment of future system. Such a process is termed the PDSA Cycle (Plan Do Study Act), the Shewhart Cycle, the PDCA (Plan Do Check Act) or the Deming Wheel. Regardless of the name, the process is an established methodology that aims at continual improvements. Cutler (1997) states that monitoring along with conventional risk assessment could be a basis for improving risk management and that a correct measurement discipline itself can create a value that outweighs its cost.

Part two – Case study

6 System description

"Knowing your system" is a prerequisite for undertaking assessments of risks. This chapter describes the water supply system in Gothenburg in general and the Lackarebäck Water Treatment Plant in detail including treatment design, the use of SCADA and diary and deviation report records.

6.1 Water treatment in Gothenburg

Göteborg Water and Wastewater Works supply drinking water in the Gothenburg area. Göta älv is being 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.

6.1.1 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. The average flow in Göta älv is 550 cubic meters per second and an approximate flow of two cubic meters per second are drawn from the river at the off-take at Lärjeholm (VA-verket, 2005). The raw water off-take is located at Lärjeholm along Göta älv as shown in Figure 8.

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 (VA-verket Göteborg, 2005). 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 (Bergstedt, 2005).

6.1.2 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 direct from Lärjeholm. The raw water for LWTP is directed from Lärjeholmen to Lake Lilla Delsjön and Lake Stora Delsjön (Figure 8). 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 (Bergstedt, 2005). 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. Figure 9 shows a flow diagram of the system.

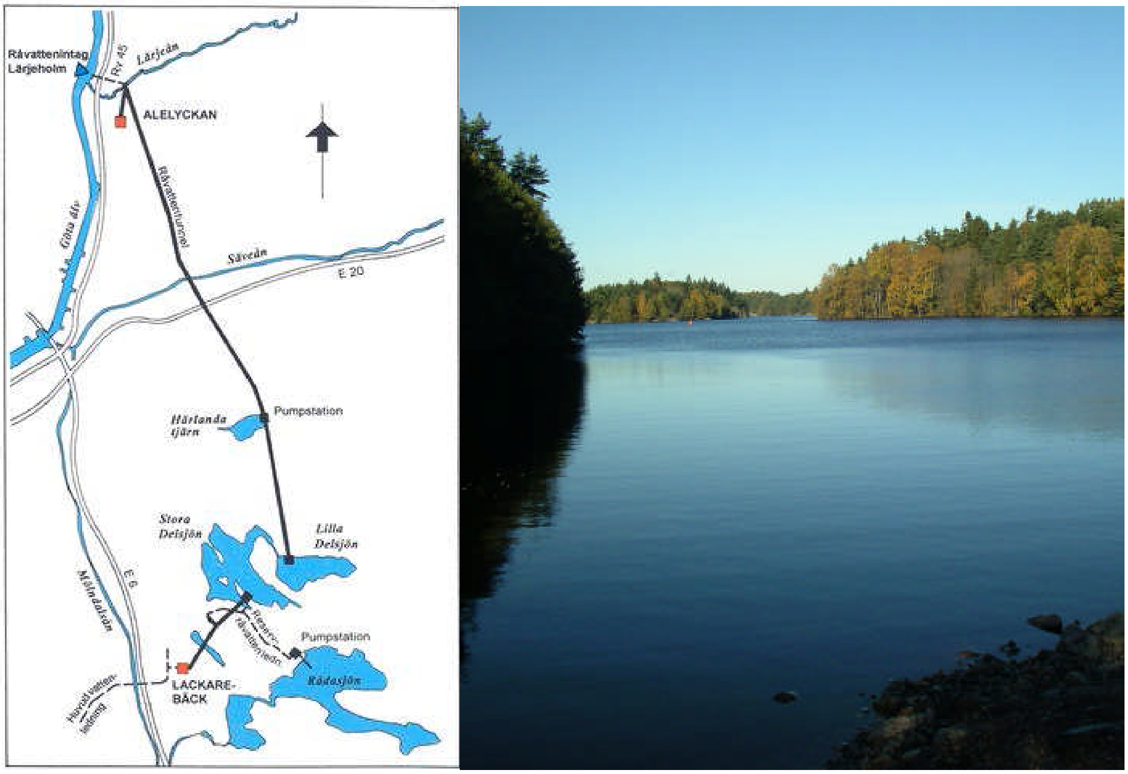

Figure 8. Left: Map of Gothenburg water supply system. Right: Lake Stora Delsjön.

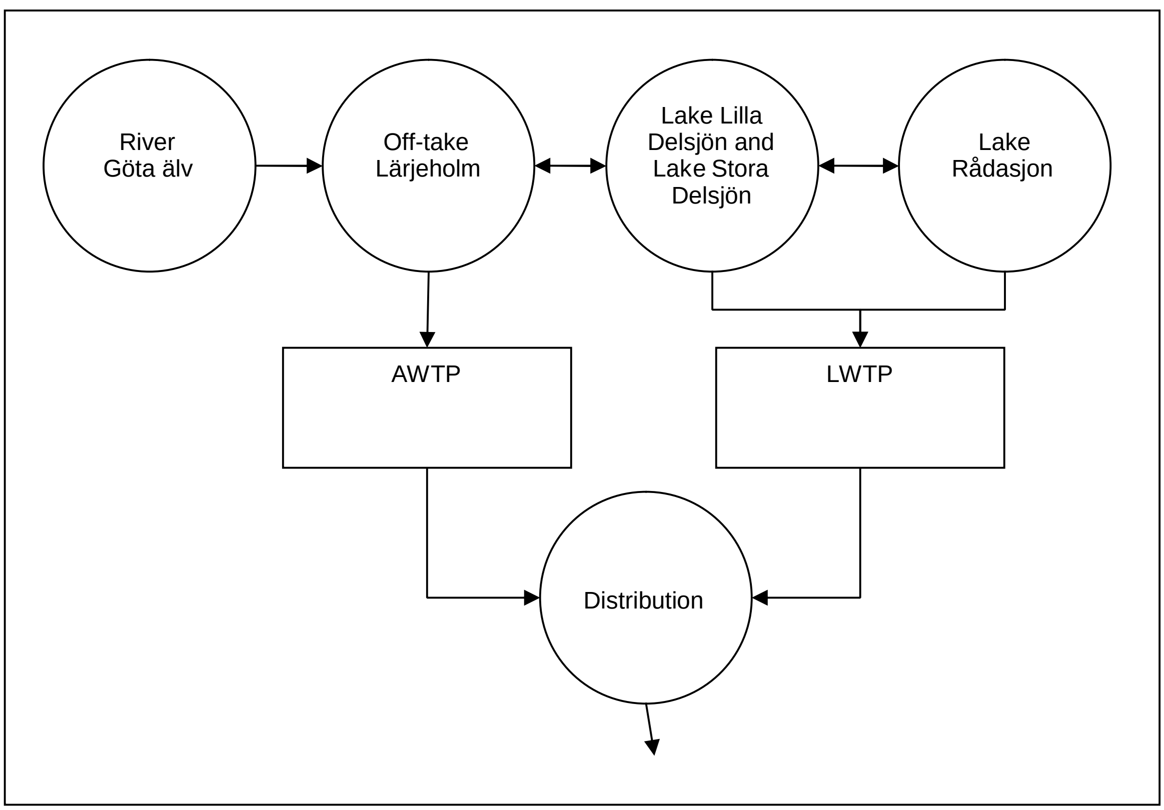

Figure 9. Schematic figure of Gothenburg water supply system

6.1.3 Lackarebäck Water Treatment Plant (LWTP)

LWTP was commissioned in 1968. The treatment train is divided into a North and South section, where the North section consists of process lines 1, 3, 5, and 7 and the South section consist of process line 4, 6, and 8 (Figure 10).

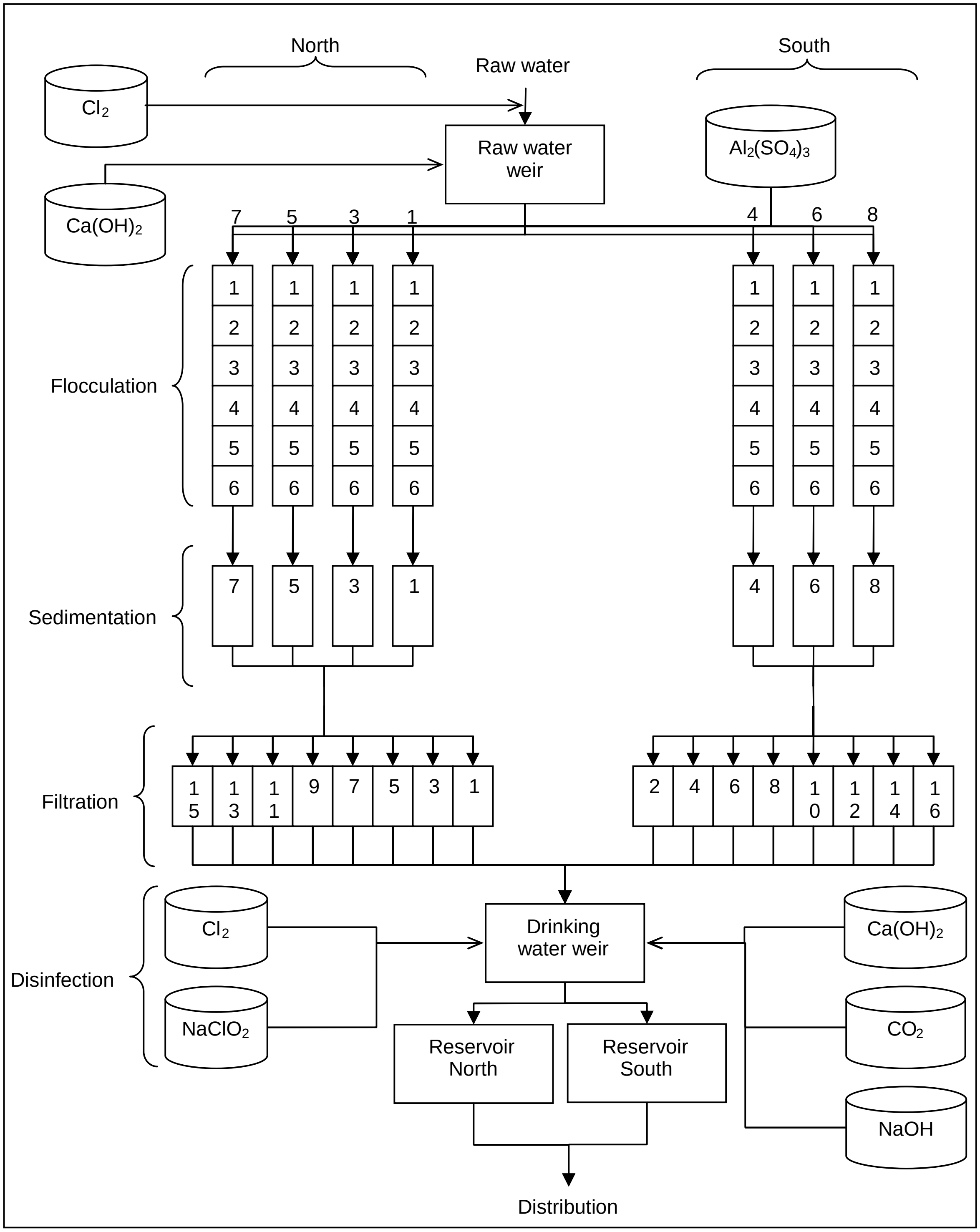

Figure 10. Process scheme LWTP (to simplify the scheme, the Cl_2 and $Ca(OH)_2$ tanks have been depicted as two separate tanks)

All process lines, except line 7 which also includes flotation, have similar design. The treatment process includes:

1. Pre dosing: pH adjustment and chlorination if the temperature exceeds 12 degrees Celsius
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 temperature, an off-take at 16 meters is used. (Olsson, 2005)

If the temperature of the raw water exceeds 12 degrees Celsius, chlorine is used in the raw water weir (Figure 11) 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. This is done to promote optimal flocculation. (Olsson, 2005)

Figure 11. 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 system with six chambers where alum is dosed in chamber one. Adding the alum lowers the pH to approximately pH 6.5. 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. 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 waste water treatment plant. The disinfection consists of Cl_2 and $NaClO_2$ dosing in the drinking water weir. (Olsson, 2005)

A raw water flow of 3400 m^3/h gives a residence time of 1.9 hours in flocculation, 4.1 hours in sedimentation and 0.5 hours in filtration. That makes a total of 6.5 hours. The residence time in the drinking water reservoir is approximately 2 to 3 hours depending on prevailing level at that time. Maintenance of turbidity meters, chlorine residual meters, and pH meters at LWTP is undertaken based on the schedule in Table 3. (Olsson, 2005)

Table 3. Maintenance at LWTP

Type of meter	Maintenance performed	Interval
Turbidity	Cleaning and adjustment	Every 2 weeks
Chlorine residual	Cleaning and change of reactant	Every 4 week or at deviation from lab value (tolerance 0.02 units)
pH	Cleaning, KCl replenishment and calibration	Every 2 weeks

6.2 SCADA at LWTP

6.2.1 Available SCADA data

A selection of SCADA parameters including turbidity, chlorine residual and pH are monitored at different locations as shown in Figure 12 in LWTP. For critical process control there are double sets of meters, one for control and one for supervision (Bergstedt, 2005). Parameters are measured every sixth second and stored as a mean value each minute. The one-minute mean values act as basis for the 10-minute mean values. The parameters are stored as:

- one-minute mean value SCADA data for one year
- 10-minute mean value SCADA data for four years
- 60-minute mean value SCADA data for seven years

Particle count and size has been sampled since 01/Jul/2005, but is not yet complete and easily accessible. It was not possible to gain turbidity data measured before and after each single filter. (Olsson, 2005)

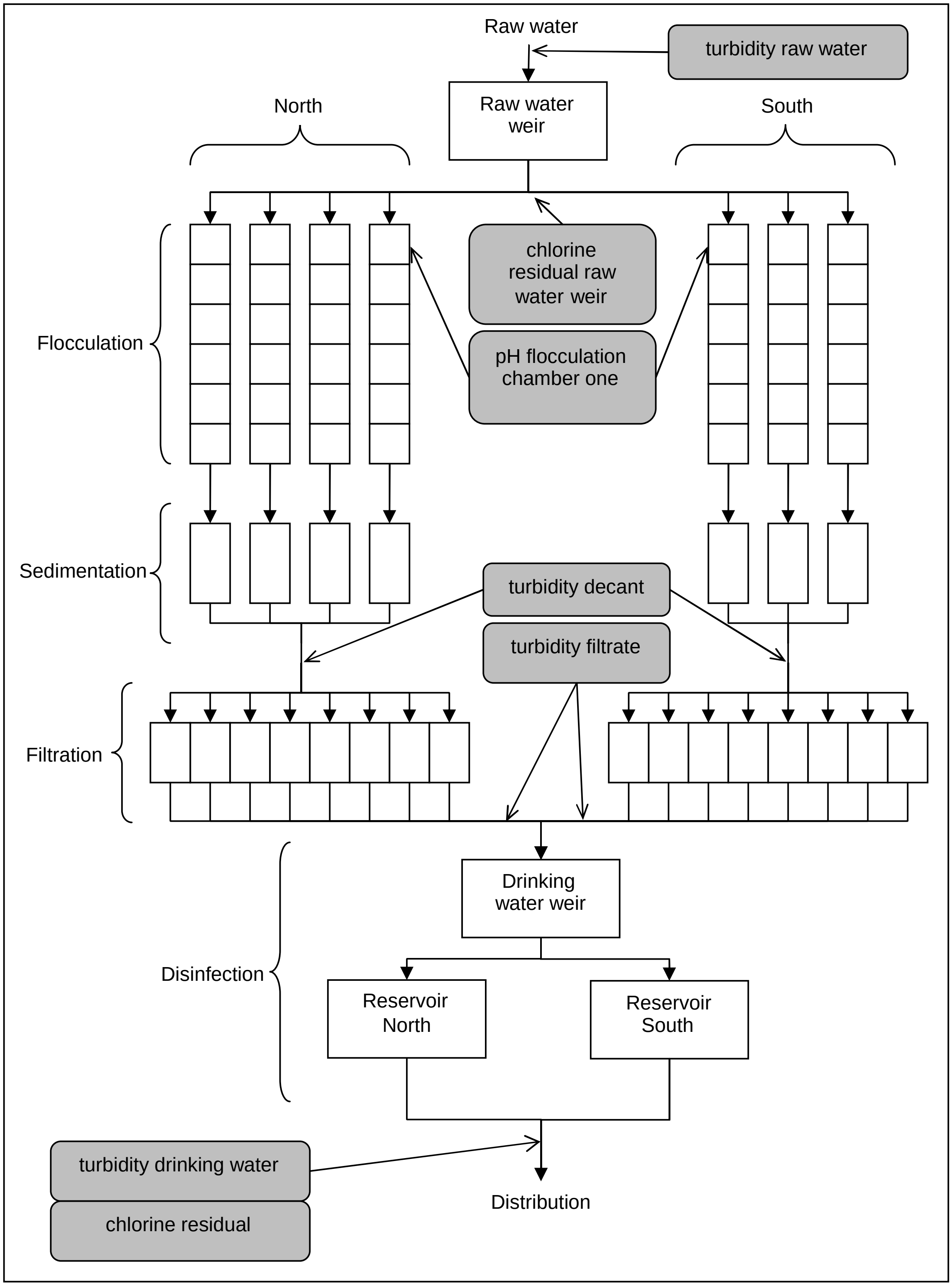

Figure 12. Monitoring points of significance to microbiological risk at LWTP

6.2.2 Current use of SCADA data at LWTP

Currently, SCADA data is used for follow-up, troubleshooting and reports at LWTP. Follow-up is undertaken to identify long term trends and as a basis for measures like improved barrier effect. Troubleshooting is made when alarm ranges are exceeded or when other indications of deviations are at hand. When this is the case, it is not only the parameter exceeding the range that is checked for, but a larger set of parameters are also examined. The reports are generated for management purposes such as quality and safety issues as well as for a basis for changes in dosing. The use of turbidity, chlorine residual and pH SCADA data is summarized in Table 4. (Bergstedt, 2005)

Table 4. Current use of selected SCADA at LWTP

Parameter	Measure point	Purpose
Turbidity	Raw water	To monitor quality of raw water
	Decant	To ensure the flocculation and sedimentation processes work properly
	Filtrate	To ensure the filtration process work properly
	Drinking water	To monitor the drinking water quality regarding turbidity
Chlorine residual	Raw water weir	To ensure raw water chlorination works properly
	Drinking water	To ensure drinking water chlorination works properly
pH	Raw water	To act as a basis to reach optimal pH before adding of alum for flocculation
	Raw water weir	To ensure adding of lime is undertaken
	Flocculation chamber one	To ensure the flocculation process works properly
	Flocculation chamber 6	To monitor when the system is working properly after flushing or after sending water to drainage. The pH measurement provides information when normal operation is on after such a deviation.
	Drinking water	To be able to avoid a pH such that corrosion of pipes occurs

6.2.3 Alarm range values for SCADA meters at LWTP

Alarm range values for selected turbidity, chlorine residual and pH meters are shown in Table 5.

Table 5. Alarm range values for turbidity, chlorine residual and pH at LWTP

Parameter	Alarm range
Turbidity raw water	0.01-1.80 FNU
Turbidity filtrate	0.01-0.40 FNU
Turbidity drinking water	0.01-0.20 FNU
Chlorine residual raw water weir	0.04-0.20 mg/L
Chlorine residual drinking water	0.12-0.38 mg/L
pH flocculation chamber one	5.90-6.95

6.3 Diary records and deviation reports at LWTP

6.3.1 Diary records

Diary records were available for time period 2002-2005. Records before 2002 are stored in a text book and are thus not easy accessible. Diary records are taken on a daily basis and cover day to day issues such as general observation, maintenance, and small incidents. For 2005, an average of almost four diary records where taken per day.

6.3.2 Deviation reports

Deviation reports are available for the time period 2001-2005 and contain extended information about major events. Major events include all kinds of events, regardless of whether microbial related, that had or could have had a major impact on the overall process. An average of ten deviation reports pertinent to microbial safety is the result of deviations each year.

7 Method of the case study

By analysing diary records and deviation reports in parallel with SCADA data, advantages and limits to SCADA data in its ability to identify hazardous events and their durations and magnitudes could be assessed. The overall methodology for the case study is shown in Figure 13.

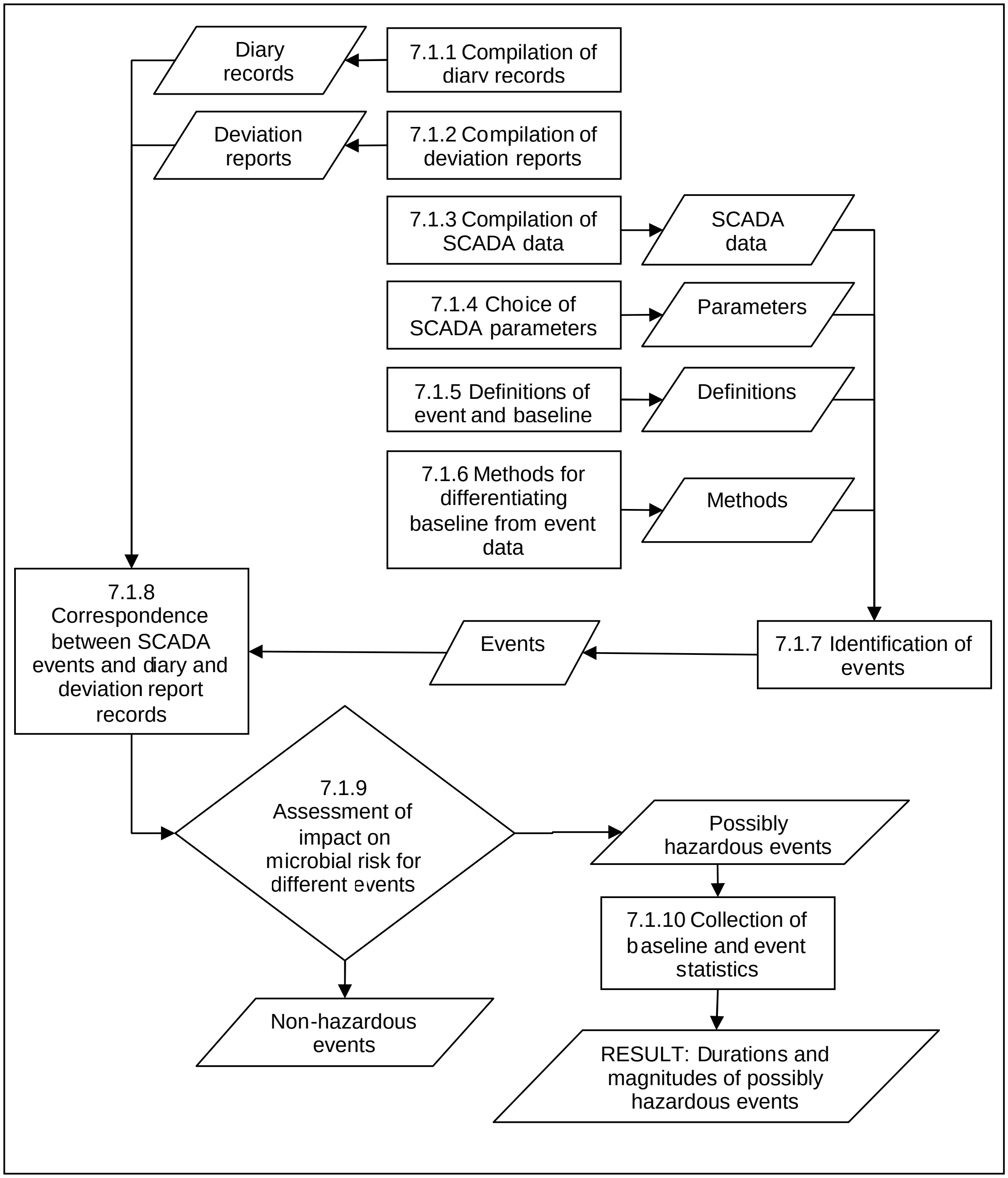

Figure 13. The overall methodology for the case study

7.1 Sequence of work

7.1.1 Compilation of diary records

Diary records were acquired as MS Excel spreadsheets. In total, 1 409 Diary records were provided for the time period 01/Oct/2004-19/Sep/2005 as shown in Table 6.

Table 6. Example of diary records

Date	Duration	Event
…		
04/Jan/2005	08:00-08:30	Cleaning of turbidity meter raw water
04/Jan/2005	11:00	Increased raw water flow from 4 200 m^3/h to 4 600 m^3/h
…		

Note: Not real data.

7.1.2 Compilation of deviation reports

Deviation reports were acquired as text files. In total, 6 Deviation Reports of possible microbiological relevance were acquired and compiled for the time period 01/Oct/2004-19/Sep/2005.

7.1.3 Compilation of SCADA data

10-minute SCADA data was acquired as text files each covering three months. The data was imported and compiled in MS Excel, each parameter covering the time period 01/Oct/2004-19/Sep/2005. This equalled sets of approximately 50,000 records which is within the upper limit of 65 536 records per MS Excel worksheet.

7.1.4 Choice of SCADA parameters

Even though there were numerous parameters to study only a few of them were of microbial relevance. As discussed in Chapter 4.2, some of the parameters such as turbidity, chlorine residual and pH had a clear relationship with removal of micro-organisms. Furthermore, Westrell *et al* (2003) reported that, for LWTP, the factors relevant for pathogen removal during treatment were coagulant dose, precipitation pH, disinfectant dose, and filtration performance. Furthermore, hydraulic retention time is of importance to microbial safety. Even though the raw water flow is measured and could, in theory, be sufficient to approximate the hydraulic retention time this factor was not included in the analysis. This can be justified due to very low surface loads and long retention times in LWTP flocculation and sedimentation processes as well as small overall process variability (Bergstedt, 2005). Taken together, measurements as shown in Table 7 were chosen for analysis. In total, the acquired SCADA data covered the time period 01/Oct/2004-19/Sep/2005.

Table 7. Rationale for choice of SCADA parameters for analysis

Parameter	Measure point	Rationale for choice
Turbidity	Raw water	Elevated values may indicate increased faecal contamination of raw water
	Filtrate water	Elevated values indicate heightened risk for water of bad microbial quality due to insufficient treatment or particle break through
	Drinking water	Even though drinking water is limed filtrate water this measurement might act as a backup
Chlorine residual	Raw water weir	Raw water chlorination prevents microbial growth in the filters and could hence have impact on microbial risk
	Drinking water	Any decreasing value significant from normal may have an impact on microbial risk
pH	Flocculation chamber one	Any significant deviation outside optimum value may have an impact on microbial risk

The 10-minute interval was a compromise between high resolution and size of the data set. As the 10-minute mean value was based upon one-minute average values, it also had the ability to detect shorter events than ten minute. However, due to the scale, shorter events had a minor impact on the 10-minute value as seen in Figure 14.

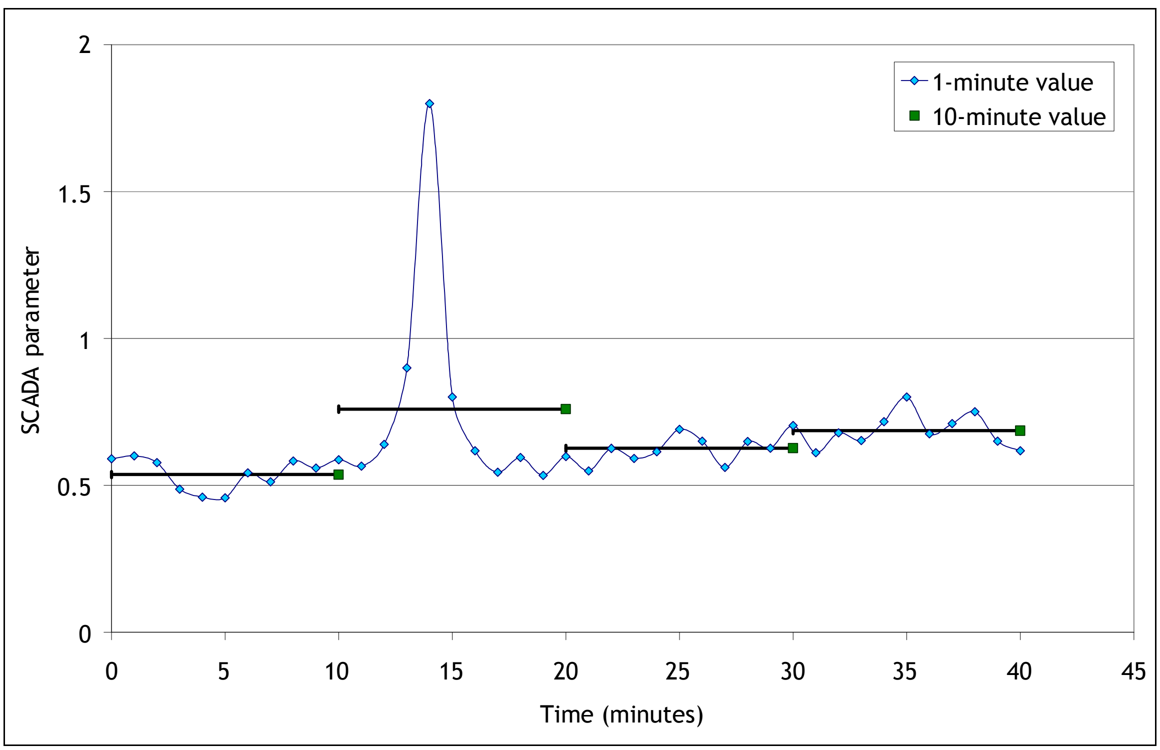

Figure 14. One-minute and 10-minute resolution data

7.1.5 Definitions of event and baseline

The definitions of a "hazard" and a "hazardous event" were put into a general perspective by Nadebaum *et al.* (2004) who defined them as:

"*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.*"

"A hazardous event is an incident or situation that can lead to the presence of a hazard."

The definition can also regard a SCADA event. As mentioned in Chapter 3.4.4, managing short events could be an efficient way of reducing health risks. This fact highlighted the need for identifying short events which were unlikely to be discovered with grab sampling. Bergstedt (2005) suggested:

"A SCADA event is an occasion that deviates from normal or even optimal."

This definition makes sense given that the 10-minute mean value is based upon the 1-minute mean value and hence will be smoothed by the 10-minute mean value as shown in Figure 14. The definition of a SCADA event as being a period with suboptimal conditions was used when identifying events.

Literature studies suggest that no consistent definition of "baseline" exists (Hirsch, 1980). Sources vary in their explanation and the meaning is strongly dependent on the context.

"Baseline is a description of conditions existing at a point in time against which subsequent changes can be detected through monitoring." (Hirsch, 1980)

"Baseline means the condition of the natural resources and services that would have existed had the incident not occurred." (OPA, 1990)

In this project, the baseline was defined as when normal or optimal values appear, i.e. when an event was not occurring. When calculating baseline statistics this definition has been circumvented and all data points have been included. This is a valid approach given that the events due to short duration have a small impact on arithmetic mean and standard deviation for the baseline.

7.1.6 Methods for differentiating baseline from event data

Splitting baseline from event data introduced the following problems:

- Some of the parameters exhibited long term trend changes. For example, turbidity as well as pH exhibited seasonal variations. This meant that the baseline, where appropriate, couldn't be set to a fixed value.
- Parameters behaved in a different way. For example, raw water turbidity corresponded to natural variation whereas chlorine residual corresponded to the set chlorine dosing and flow.

To address the problems described above, different approaches to differentiate baseline from event data were applied to the data sets. The analysis was carried out by:

- Empirical observation
- Identification of deviation outside given range (e.g. set range or 99th percentile)
- Identification of significant change in time series statistics

Initially, the data plots were examined in blocks of one week. This was a good way to plot data behavior but many problems were associated with this method such as time demands and extensive work loads. The most efficient empirical way of splitting events from baseline was by:

- Plotting 3 months of values on a chart
- Identifying events empirically; to be classified as an event it must consist of a 'distinct' deviation from ambient values.
- Tabulating the event attributes by hand

Deviation outside a given range was investigated as an alternative approach. The studied parameters had a set target range as stated in Table 5. The one-minute mean value could exceed the target range at the same time as the 10-minute mean value did not. The 10-minute mean value seldom or never exceeded the target range. As a result of this, an event could still be at hand even if the target range was not exceeded by the 10-minute mean value. If the parameter lacked long term variation it could be suitable for detecting events by narrowing the target range to a set range or by applying baseline statistics as the 99^{th} percentile as a range. Deviations outside the given range were then considered being events. The number of the events detected was then solely dependent on the width of the range. This method is a variant of Shewhart's general model for control charting.

As a final method, change in time series statistics was evaluated. There are numerous ways of interpreting time series (Rodionov, 2005). From literature studies it was clear that the CUSUM approach was of interest.

7.1.7 Identification of events

The data was browsed and events were identified under conditions stated in Table 8.

7.1.8 Correspondence between SCADA events and diary and deviation report records

Date and time for identified events were compared to adjacent diary and deviation report records. Different types of events appeared in the SCADA data as shown in Table 9.

7.1.9 Assessment of impact on microbial risk for different events

Each event was assessed using the question: Is the event of possible impact on microbial risk? The answer to this question could be 'yes' or 'no'. If the answer was positive this event was classified as a 'possibly hazardous event' and further statistics was collected. If the answer was negative no further studies of the event was pursued. The assessment of impact on microbial risk was a subjective measurement based on expert opinions as by Bergstedt (2005) and Roser (2005). The assessment was made in a conservative way where an event for which the microbial risk was uncertain was classified as 'possibly hazardous event'.

7.1.10 Collection of baseline and event statistics

Event statistics was collected for all events being assessed as 'possibly hazardous events'. For each of these events data as shown in Table 10 was collected. The appearance of the events and event statistics is further explained in Figure 15.

Table 8. Rationale for event identification

Parameter	Method for identification	Condition
Turbidity raw water	By empirical methods	Events detected by empirical methods
	By change in time series	Events detected by change in CUSUM control charting
Turbidity filtrate water north	By deviation outside given range	Event at hand if turbidity value exceeded 0.20 FNU
	By change in time series	Long term trends picked up by CUSUM control charting
Turbidity filtrate water south	By deviation outside given range	Event at hand if turbidity value exceeded 0.20 FNU
	By change in time series	Long term trends picked up by CUSUM control charting
Turbidity drinking water	By deviation outside given range	Event at hand if turbidity value exceeded 0.20 FNU
Chlorine residual raw water weir	By deviation outside given range	Event at hand if the chlorine residual value decreased more than 0.05 mg/L from ambient values.
	By change in time series	Long term trends picked up by CUSUM control charting
Chlorine residual drinking water	By deviation outside given range	Event at hand if chlorine residual value was less than 0.10 mg/L
pH flocculation chamber one north	By deviation outside given range	Event at hand if the deviation exceeded more than 5 standard deviations
pH flocculation chamber one south	By deviation outside given range	Event at hand if the deviation exceeded more than 5 standard deviations

Table 9. Event classification

Event classification	Abbreviation	Explanation
Maintenance in diary	MD	Day to day maintenance such as cleaning and calibration of meters, shift of pipes and pumps etc
Maintenance probable	MP	If the SCADA data appeared to be similar to SCADA data at MD events but no corresponding diary entry was to be found
Incident in diary	ID	If the event could be found in Diary records. For example pump shut-down due to power cut.
Incident in report	IR	If the event could be found in a Deviation Report. For example chlorine dosing shut-down due to malfunctioning instruments.
Unknown	UK	If the event was of unknown cause

Table 10. Statistics collected for events

Statistics	
Maximum	Maximum value for event as defined in Figure 15
Arithmetic mean	The arithmetic mean of event points as defined in Figure 15
Minimum	Minimum value for event as defined in Figure 15
Standard deviation	The standard deviation of event point as defined in Figure 15
Duration	Duration of event as defined in Figure 15
Number of measurements	The number of event points as defined in Figure 15

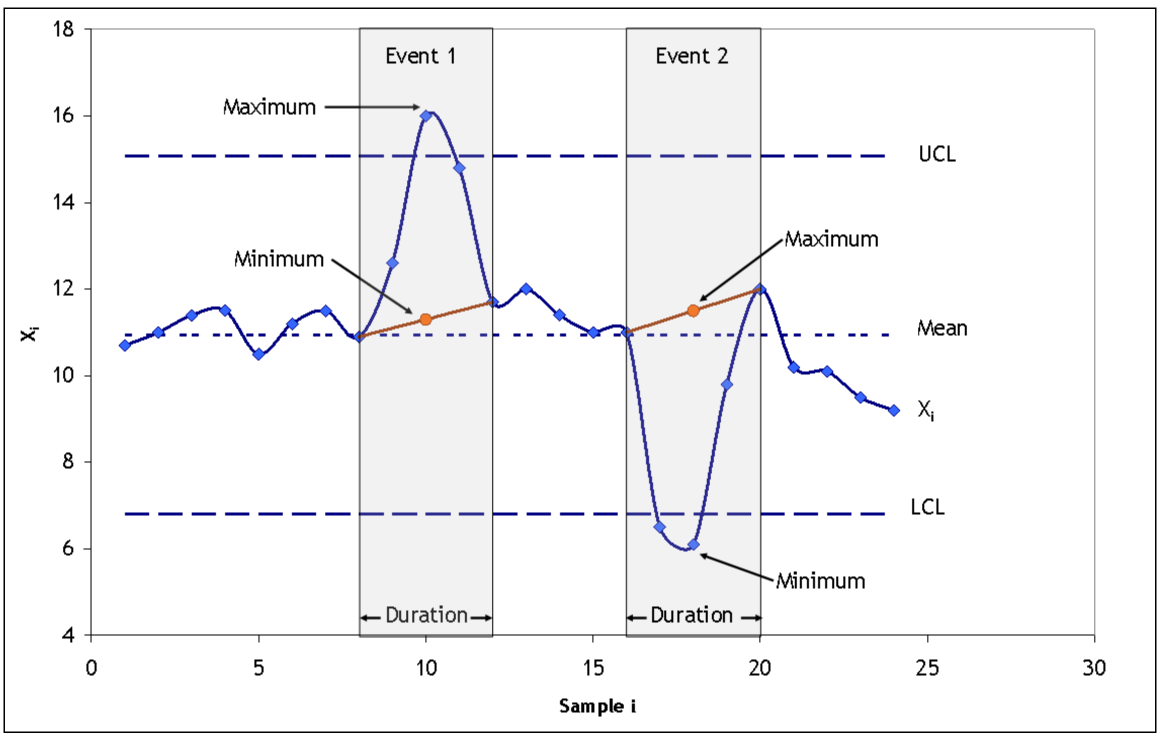

Figure 15. Definition of event statistics. The figure depicts two events; one for increased values (Event 1) and one for decreased values (Event 2). Event points are those points that together constitute an event (shaded area). (UCL = Upper Control Limit, LCL = Lower Control Limit, Mean = Arithmetic mean of all samples, X_i *= Value for parameter X in sample i)*

8 Results of the case study

8.1 Overall

The overall SCADA event statistics are shown in Table 11. From the overall result it was clear that:

- In total, 119 events was identified
- 85 (71 %) were considered being non hazardous; of the 85 non hazardous events 72 (85 %) were considered being the result of maintenance and 13 (15 %) being the result of incidents
- 34 (29 %) were considered being possibly hazardous; of the 34 possibly hazardous events 26 (76 %) were of unknown cause and the 8 (24 %) others caused by maintenance or incidents

Table 11. Overall SCADA event statistics

	Non hazardous	Possibly hazardous
Number of maintenance or probable maintenance events	72	2
Number of incidents in diary	13	3
Number of incidents in report	0	3
Number of unknown events	0	26
Total number of identified events	**85**	**34**

8.2 Turbidity statistics

Baseline statistics for raw water, filtrate water and drinking water turbidity are shown in Table 12. From the baseline statistics it was clear that:

- Raw water turbidity had an arithmetic mean of 1.01
- Filtrate water and drinking water turbidity was very low with a arithmetic mean of 0.03 and 0.04 respectively

Table 12. Baseline statistics for turbidity (01/Oct/2004-19/Sep/2005)

	Raw water turbidity (FNU)	Filtrate water turbidity (FNU)		Drinking water turbidity (FNU)
		North	*South*	
Arithmetic mean	1.01	0.03	0.03	0.04
Standard deviation	0.19	0.01	0.01	0.02
Number of measurements	50 975	50 975	50 975	50 975

Note:
1. This table is based upon Appendix B - Table 1.
2. FNU = Formazin Nephelometric Unit

Event statistics for raw water, filtrate water and drinking water turbidity is shown in Table 13. From the turbidity event statistics it was clear that most hazardous events were classified as of unknown cause.

Table 13. Event statistics for turbidity (01/Oct/2004-19/Sep/2005)

Event classification	Number of turbidity events in raw water (n)		Number of turbidity events in filtrate water (n)				Number of turbidity events in drinking water (n)	
			North		*South*			
	Non-hazardous	Possibly hazardous	Non-hazardous	Possibly hazardous	Non-hazardous	Possibly hazardous	Non-hazardous	Possibly hazardous
Maintenance in diary (MD)	8	0	6	1	10	1	12	0
Maintenance probable (MP)	15	0	0	0	0	0	0	0
Incident in diary (ID)	0	0	0	0	0	0	3	0
Incident in deviation report (IR)	0	0	0	0	0	0	0	0
Unknown (UK)	0	6	0	10	0	1	0	2
Events found	**23**	**6**	**6**	**11**	**10**	**2**	**15**	**2**

The frequency, magnitude and duration for possibly hazardous turbidity events are summarized in Table 14. It was clear that:

- Most turbidity events were of short term with a duration between 0.3 and 1.3 hours
- The raw water turbidity event with a duration of 46 days was likely to be due to algae bloom
- The filtrate water turbidity event with a duration of 115 days corresponded to shut down of pre-chlorination
- The north production line had considerably more events than the south production line
- The raw water turbidity event lasting 34 hours was of special interest as to the long duration

Table 14. Date, time, magnitude and duration for possibly hazardous turbidity events (01/Oct/2004-19/Sep/2005)

Location of event	Type of event	Date and time	Maximum (FNU)	Arithmetic mean (FNU)	Minimum (FNU)	Duration (hours)	Number of 10-min measurements (n)
Raw water	UK	09/Jan/2005 02:30	1.26	1.20	0.98	34	206
	UK	15/Mar/2005 10:30	1.64	1.20	0.98	1.3	9
	UK	26/Mar/2005 00:00*	1.96	1.37	0.98	1 093 (46 days)	6 558
	UK	02/Sep/2005 10:30	1.43	1.12	0.99	0.7	5
	UK	09/Sep/2005 13:20	1.42	1.14	1.02	0.7	5
Filtrate water north	MD	01/Feb/2005 00:00*	0.44	0.05	0.03	2 759 (115 days)	16 554
	UK	03/Feb/2005 09:40	0.21	0.15	0.11	0.7	5
	UK	10/Feb/2005 08:00	0.21	0.13	0.09	0.8	6
	UK	10/Feb/2005 15:20	0.26	0.17	0.10	0.8	6
	UK	24/Feb/2005 03:10	0.23	0.15	0.11	1.0	7
	UK	24/Feb/2005 12:10	0.22	0.15	0.10	0.7	5
	UK	24/Feb/2005 19:50	0.21	0.14	0.11	1.0	7
	UK	25/Feb/2005 22:30	0.24	0.15	0.10	0.8	6
	UK	28/Feb/2005 22:30	0.21	0.14	0.10	1.0	7
	UK	28/Jun/2005 10:10	0.28	0.11	0.02	0.3	3
	UK	04/Sep/2005 21:20	0.32	0.13	0.03	0.7	5
Filtrate water south	MD	01/Feb/2005 00:00*	0.40	0.04	0.03	2 759 (115 days)	16 554
	UK	28/Feb/2005 20:20	0.21	0.15	0.11	0.8	6
Drinking water	UK	02/Jun/2005 12:30	0.58	0.18	0.04	0.5	4
	UK	28/Jun/2005 10:10	0.49	0.14	0.03	0.7	5

Note:
1. UK = Unknown
2. MD = Maintenance in diary
*3. * = Event detected solely by CUSUM.*

Figure 16 shows raw water turbidity SCADA data with identified events for the time period 01/Jan/2005-31/Mar/2005. This is a good example of the appearance of raw water turbidity characterized by sudden spikes probably due to maintenance, and unknown spikes which were considered as possible hazardous events if no correspondence with diary records was found.

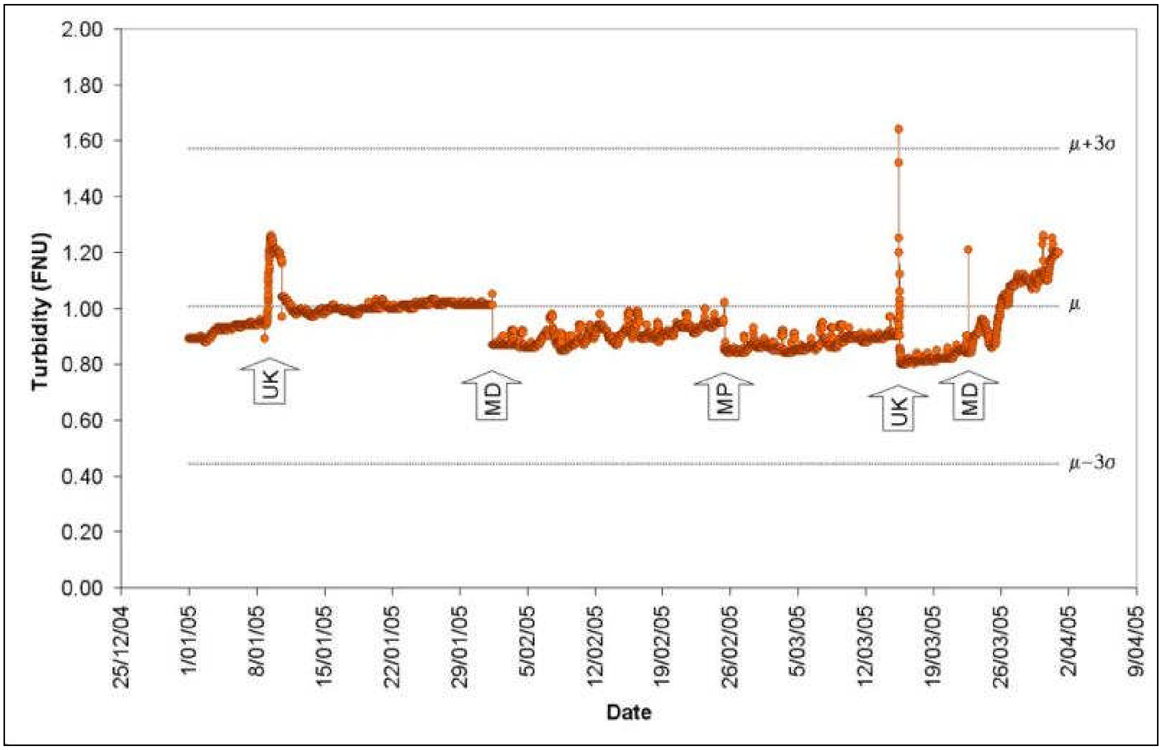

Figure 16. Raw water turbidity SCADA data with identified non-hazardous and possibly hazardous events (UK = Unknown event, MD = Maintenance in diary event, MP = Maintenance probable event)

Figure 17 shows raw water turbidity SCADA data with a long term trend, possibly algae bloom, picked up by CUSUM control charting. The minimum and maximum values of the CUSUM control chart constitute change points. The change points are where the algae bloom starts and ends respectively. This is a good example of a parameter with seasonal variation. The elevated values during the algae bloom period are greater than those originating from isolated spikes. This fact makes it hard to detect event on the basis of a given limit. Instead, events were in this case identified empirically, that is by significant deviation from ambient values.

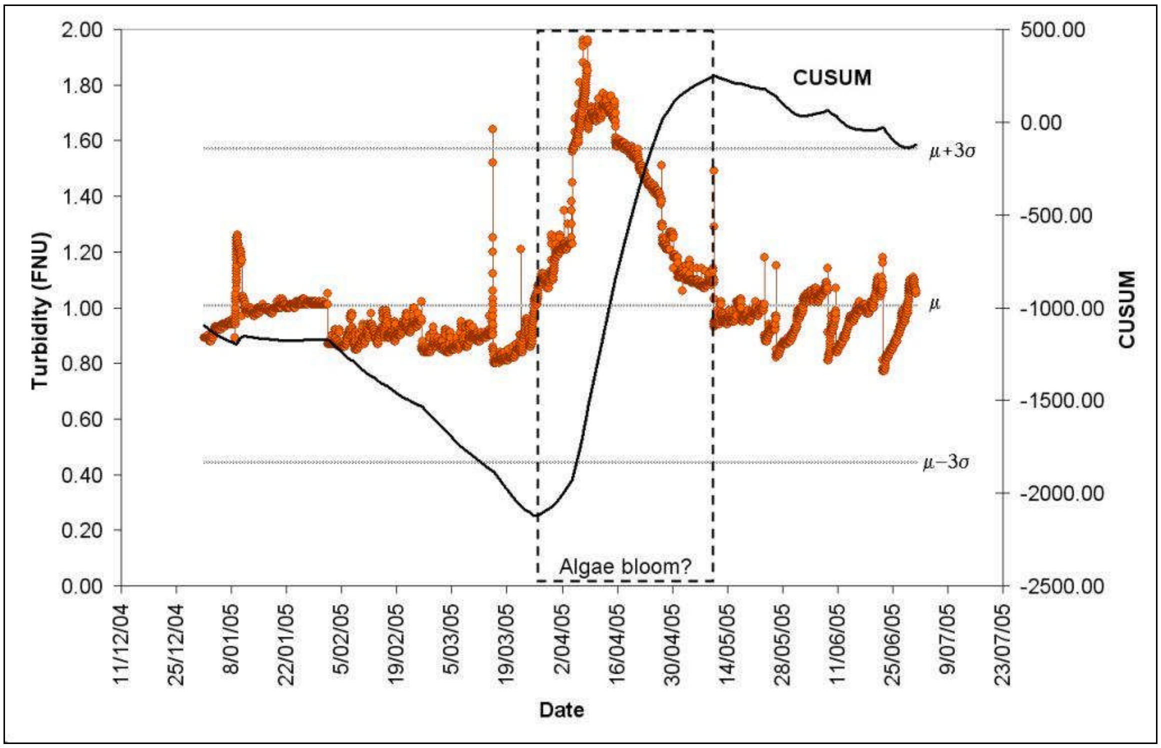

Figure 17. Raw water turbidity SCADA data with CUSUM

Figure 18 shows filtrate water turbidity SCADA data with CUSUM and upper control limit (UCL). The appearance of the filtrate water turbidity was somewhat different to the raw water turbidity. As seen in the figure the spikes frequently exceed the $\mu+3\sigma$ limit and the spikes seem to be of short term rather than long term. All points exceeding the UCL were considered being events. The CUSUM picked up a change point which corresponded to pre-chlorination shut off.

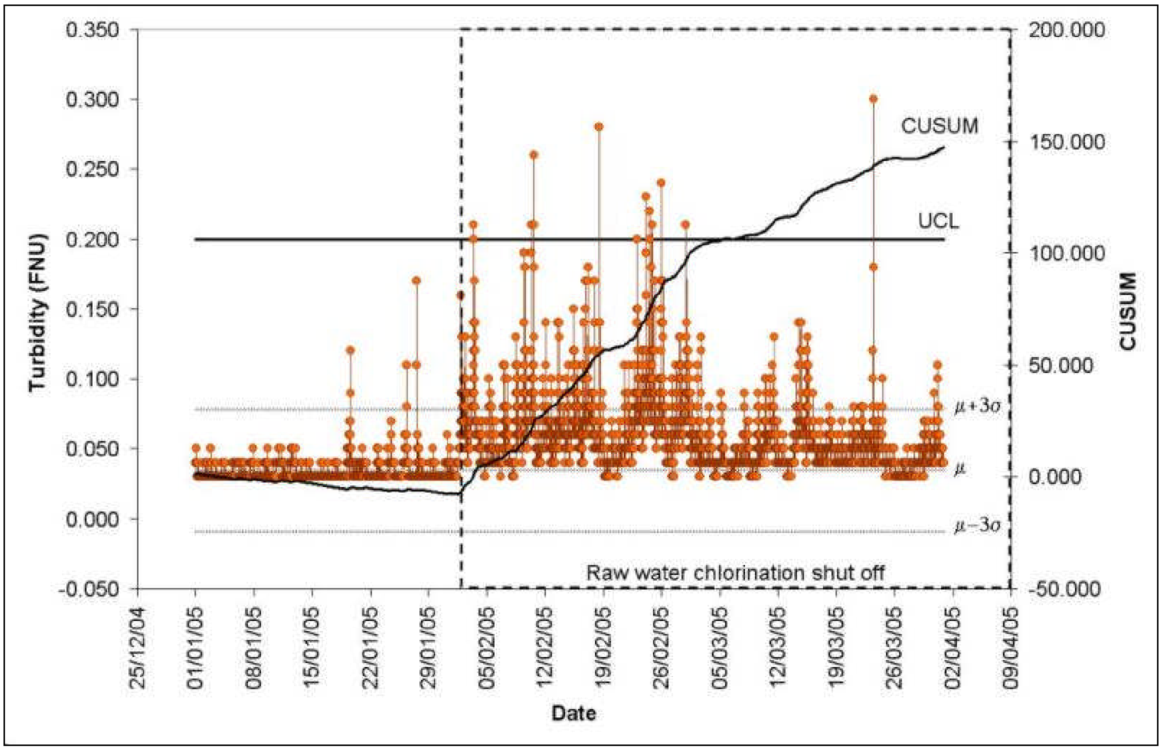

Figure 18. Filtrate water turbidity SCADA data with CUSUM and UCL

8.3 Chlorine residual statistics

Baseline statistics for chlorine residual in raw water weir and drinking water are shown in Table 15. From the baseline statistics it was clear that:

- Raw water weir chlorine residual had an arithmetic mean of 0.06 mg/L and a standard deviation of 0.04 mg/L. As the raw water chlorination is shut down during certain periods of the year this parameter only comprised 38595 records.
- Drinking water chlorination had an arithmetic mean of 0.20 mg/L and a standard deviation of 0.04 mg/L

Table 15. Baseline statistics for chlorine residual (01/Oct/2004-19/Sep/2005)

	Raw water weir chlorine residual (mg/L)	Drinking water chlorine residual (mg/L)
Arithmetic mean	0.06	0.20
Standard deviation	0.04	0.04
Number of measurements	38 595	50 975

Note: This table is based upon Appendix C - Table 1 in Appendix C

Event statistics for raw water weir and drinking water chlorine residual are shown in Table 16. From the chlorine residual statistics it was clear that most hazardous events were of unknown cause.

Table 16. Event statistics for chlorine residuals (01/Oct/2004-19/Sep/2005)

Event classification	Number of chlorine residual events in raw water weir (n)		Number of chlorine residual events in drinking water (n)	
	Non-hazardous	Possibly hazardous	Non-hazardous	Possibly hazardous
Maintenance in diary (MD)	4	0	1	0
Maintenance probable (MP)	0	0	0	0
Incident in diary (ID)	3	0	6	0
Incident in deviation report (IR)	0	1	0	0
Unknown (UK)	0	5	0	1
Events found	**7**	**6**	**7**	**1**

The frequency, magnitude and duration for possibly hazardous chlorine residual events are summarized in Table 17. It is clear that:

- 5 possibly hazardous events were identified in the raw water weir and 1 possibly hazardous event was identified in the drinking water weir
- All events were of short term ranging from 0.3 to 2.3 hours

Table 17. Date, time, magnitude and duration for possibly hazardous chlorine residual events (01/Oct/2004-19/Sep/2005)

Location of event	Type of event	Date and time	Maximum (mg/L)	Arithmetic mean (mg/L)	Minimum (mg/L)	Duration (hours)	Number of 10-min measurements (n)
Raw water weir	UK	15/Oct/2004 08:10	0.08	0.03	0	2.3	15
	UK	11/Jul/2005 15:10	0.09	0.07	0.03	0.3	3
	UK	16/Jul/2005 10:50	0.10	0.08	0.04	0.5	4
	IR	13/Aug/2005 05:00	0.12	0.09	0.05	0.5	4
	UK	27/Aug/2005 10:20	0.09	0.07	0.03	0.5	4
Drinking water	UK	09/Sep/2005 10:30	0.26	0.16	0.00	0.8	6

Note:
1. UK = Unknown
2. IR = Incident in report

Figure 19 shows drinking water chlorine residual SCADA data with identified events for time period 01/Jul/2005-19/Sep/2005. The appearance of drinking water chlorine residual SCADA data was characterized by spikes. All points falling short of the lower control limit (LCL) were considered to constitute an event. In this case, three out of four spikes had correspondence in diary (ID and MD) and were considered as non-hazardous.

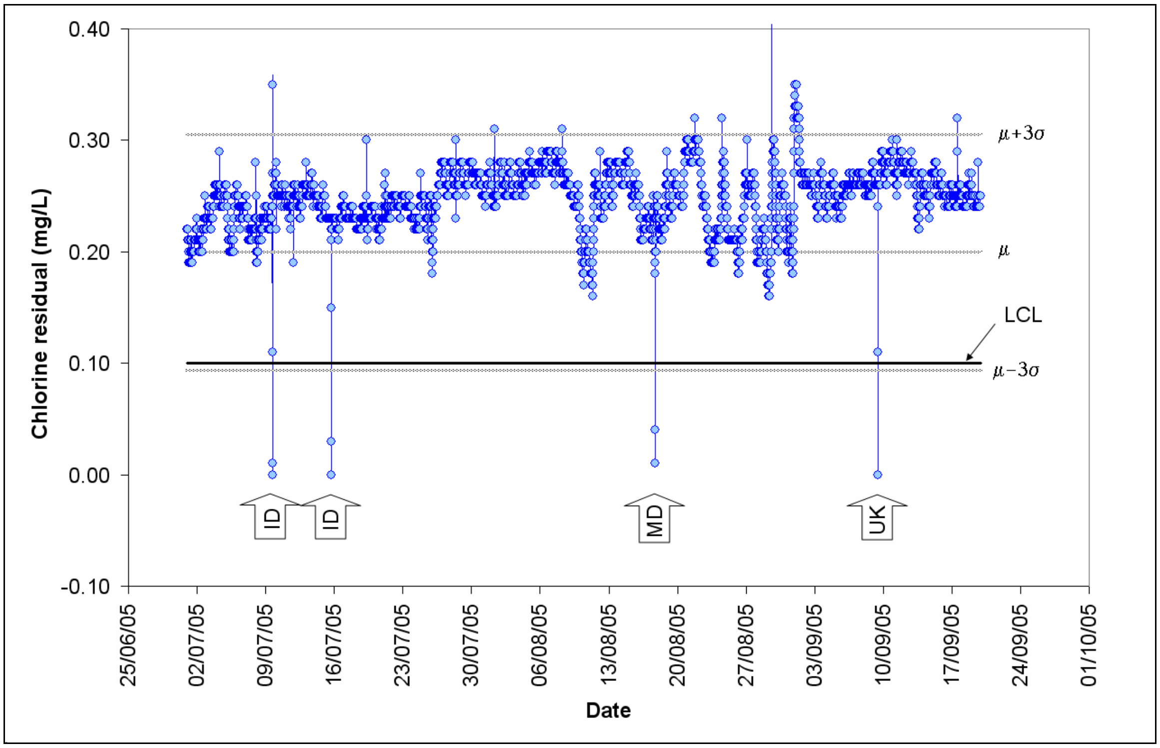

Figure 19. Drinking water chlorine residual SCADA data with identified non-hazardous and possibly hazardous events (ID = Incident in diary event, MD = Maintenance in diary event, UK = Unknown event)

8.4 pH statistics

Baseline statistics for flocculation pH is shown in Table 18. From the baseline statistics it was clear that:

- The north and the south system showed similar appearance with an arithmetic mean around pH 6.5
- The standard deviation of pH 0.05 was very low which indicates a stable process

Table 18. Baseline statistics for pH (01/Oct/2004-19/Sep/2005)

	Flocculation chamber one pH	
	North	*South*
Arithmetic mean	6.53	6.50
Standard deviation	0.05	0.05
Number of measurements	50 975	50 975

Note: This table is based upon Appendix D - Table 1 *in Appendix D*

Event statistics for pH in flocculation chamber one is shown in Table 19. From the turbidity event statistics it was clear that the hazardous events were of different origin.

Table 19. Event statistics for pH (01/Oct/2004-23/Sep/2005)

	Number of pH events in flocculation chamber one (n)			
	North		*South*	
	Non-hazardous	Possibly hazardous	Non-hazardous	Possibly hazardous
Maintenance in diary (MD)	6	0	10	0
Maintenance probable (MP)	0	0	0	0
Incident in diary (ID)	0	1	1	2
Incident in deviation report (IR)	0	1	0	1
Unknown (UK)	0	0	0	1
Events found	**6**	**2**	**11**	**4**

Frequency, magnitude and duration for possibly hazardous pH events are summarized in Table 20. It is clear that all events are of short term ranging 0.3-1.5 hours.

Table 20. Date, time, magnitude and duration for possibly hazardous pH events (01/Oct/2004-23/Sep/2005)

Location of event	Type of event	Date and time	Maximum (pH)	Arithmetic mean (pH)	Minimum (pH)	Duration (hours)	Number of 10-min measurements (n)
Flocculation chamber one north	IR	20/Jan/2005 08:20	6.97	6.74	6.54	1.5	10
	ID	27/Feb/2005 11:20	6.45	6.37	6.25	0.5	4
Flocculation chamber one south	UK	22/Dec/2004 13:50	6.77	6.59	6.52	0.5	4
	IR	20/Jan/2005 08:20	6.97	6.69	6.46	1.0	7
		20/Jan/2005 09:30	6.53	6.28	5.94	1.2	8
	ID	27/Feb/2005 06:40	6.45	6.37	6.22	0.5	4
	ID	27/Feb/2005 11:20	6.33	6.25	6.10	0.3	3

Note:

1. IR = Incident in report

2. ID = Incident in diary

3. UK = Unknown

Figure 20 shows pH SCADA data for flocculation chamber one for the north system with identified events for time period 01/Jan/2005-31/Mar/2005. Occasions when one or several coherent points falling short of the lower control limit (LCL) or exceeding the upper control limit (UCL) were considered being events. This is a good example of the appearance of pH in flocculation chamber one characterized by spikes.

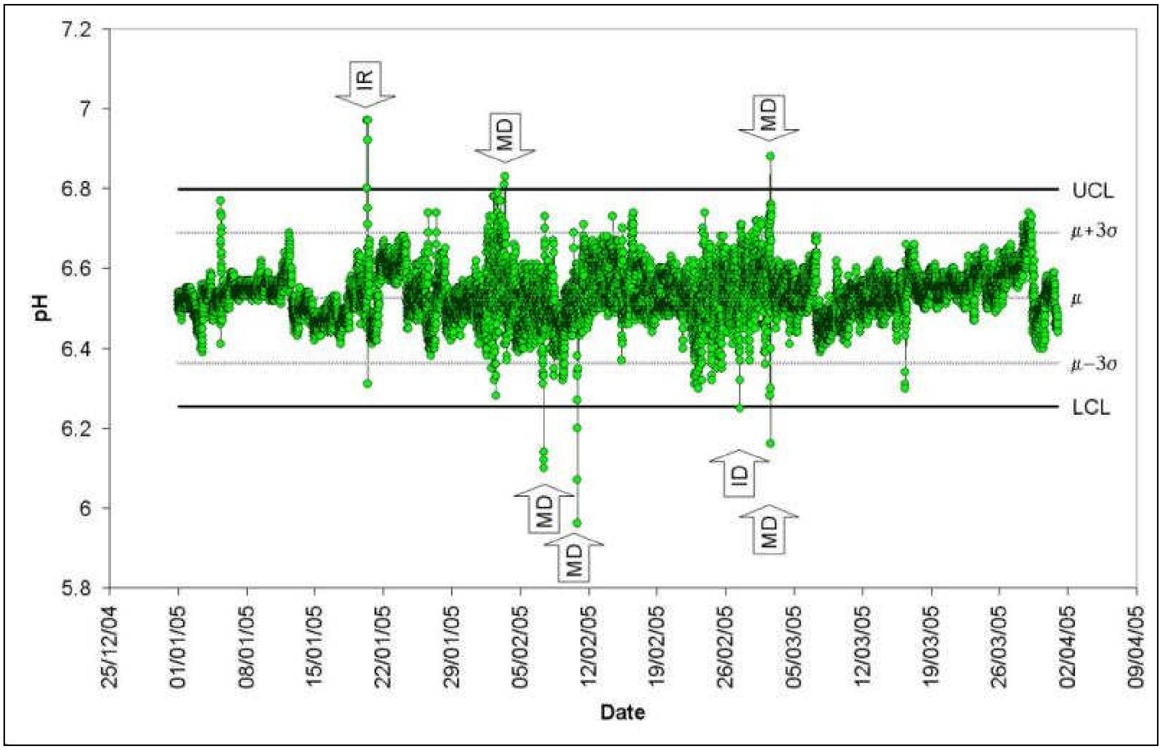

Figure 20. pH flocculation chamber one, system north, SCADA data with identified non-hazardous and possibly hazardous events (IR = Incident in report event, MD = Maintenance in diary event, ID = Incident in diary event)

8.5 Summary of possibly hazardous events

A summary of all possibly hazardous events is shown in Table 21. Under the assumption that long term events such as algae bloom were not taken into account, it was clear that occurrence of simultaneous events in multiple locations was at hand once at 28/Jun/2005. Simultaneous events in the same location, for example at 20/Jan/2005 in the flocculation chamber one in system north and system south, has not been classified as a simultaneous event. The rationale for not doing this is that system north and south are subsets of the main flow, that is the same raw water is distributed to system north (approximate 4/7) and to system south (approximate 3/7).

Table 21. Summary of possibly hazardous events

Date	Time	Location						
		Raw water	Raw water weir	Flocculation chamber one north	Flocculation chamber one south	Filtrate water north	Filtrate water south	Drinking water
15/Oct/2004	08:10		CrUK					
22/Dec/2004	13:50				pHUK			
09/Jan/2005–10/Jan/2005	02:30 - +15:00	TUK						
20/Jan/2005	08:20			pHIR	pHIR			
	09:30				pHIR			
01/Feb/2005–26/May/2005	00:00 - ++24:00					TMD	TMD	
03/Feb/2005	09:40					TUK		
10/Feb/2005	08:00					TUK		
	15:20					TUK		
24/Feb/2005	03:10					TUK		
	12:10					TUK		
	19:50					TUK		
25/Feb/2005	22:30					TUK		
27/Feb/2005	06:40				pHID			
	11:20			pHID	pHID			
28/Feb/2005	20:20						TUK	
	22:30					TUK		
15/Mar/2005	10:30	TUK						
26/Mar/2005–10/May/2005	00:00 - ++14:00	TUK						
02/Jun/2005	12:30							TUK
28/Jun/2005	10:10					TUK		TUK
11/Jul/2005	15:10		CrUK					
16/Jul/2005	10:50		CrUK					

13/Aug/2005	05:00		CrIR					
27/Aug/2005	10:20		CrUK					
02/Sep/2005	10:30	TUK						
04/Sep/2005	21:20					TUK		
09/Sep/2005	10:30							CrUK
	13:20	TUK						

Note:
1. + = One day after
2. ++ = Several days after
3. TMD = Turbidity event maintenance in diary
4. TUK = Turbidity event unknown
5. CrUK = Chlorine residual event unknown
6. CrIR = Chlorine residual event incident in report
7. pHIR = pH event incident in report
8. pHID = pH event incident in diary
9. pHUK = pH event unknown

9 Discussion of the results of the case study

9.1 Specific findings

On initial consideration, the concept of hazardous events seemed useful. However, the definition of hazardous events as those incidents or situations that can contribute to the presence of a hazard was not readily applicable to SCADA events. The parameters chosen for analysis all had relevance to microbial risk. However, as it is not clear at what levels the parameters become significant to microbial risk, the rationale for identification of events was not strictly scientifically underpinned. Consequently, the aim instead was to identify and quantify potential worst case events for each parameter.

SCADA data time series differ greatly in appearance and hence also in the way they could be analysed and interpreted. Seasonal variations and difference in variability are the two main divergences. Raw water turbidity was the only parameter that could reveal hazardous microbial events in the raw water. All other studied parameters referred to the status of the process performance. However, with the starting point that the raw water always contains pathogenic micro-organisms, it is likely that suboptimal process performance will result in a health risk.

The diary records and the deviation reports provided information about identified events in approximately 65 % of the cases. However, only a small fraction of the events are identified from deviation reports. Instead, most of the identified events are listed in the diary. This fact highlights the importance of diary entries. Diary records with a time reference was in most cases easy to connect with events identified in the SCADA records.

As shown by the results, maintenance or probable maintenance corresponds to a high proportion (approximately 60 %) of the non hazardous events. It is also clear that approximately three quarters of the possibly hazardous events were of unknown cause. Being of unknown cause is not the same as being hazardous. Rather, these events can also be due to for example maintenance that has not been reported. Underreporting of maintenance events may result in more unknown events further increasing the workload for the interpreter and leading to an overestimation of the risk. Ideally, SCADA time series analysis should be carried out on a real-time basis to identify events when they occur. Operators could then take action as they will be asked for a diary entry. This will decrease the number of unknown events.

The duration of the identified events, with few exceptions, all ranged between 0.5 and 2.3 hours. Hence, summarized over a year the total event period for various processes in the plant only takes up a short time (<1 day). The few exceptions constitute periods of possible algae bloom and adjustment of disinfectant dosing etc. lasting for much longer time (1-2 months).

The quantification of the events is based upon more than 100 events. SCADA data provides an accurate measurement of duration, magnitude and frequency of events. Uncertainties associated with the analysis of the events are hence likely to have a minor impact on the results. However, the assessment of each event's impact on microbial risk stating if it is hazardous or non-hazardous is a subjective measurement. To undertake this assessment expert opinions and conservative assumptions have been used. Still, one can not disregard this adds uncertainty to the results.

From literature studies it was evident that the CUSUM approach have potential for use, and it subsequently emerged as a useful means of identifying long term events such as probable algae bloom or adjustment of dosing levels. It also detected elevated value for filtrate turbidity when raw water chlorination was shut down. Hence, even though the raw water chlorination isn't added to act as a pre-oxidation matter but to prevent microbial growth in the filters it seems as it also has a marginal effect as a pre-oxidiser as elevated filtrate turbidity appeared when it was shut down.

Even though data from approximately one year was studied, this is as to my opinion too short a period of time to give a complete picture of frequency, duration and magnitude of hazardous events and to make predictions of future behaviour. For example, only one event concerning drinking water chlorine residual was detected in LWTP.

Concurrent events could constitute a serious threat as it weakens the protection provided by the multiple barrier concept. In drinking water production the multiple barrier concept is vital. As the barriers are not independent of each other it is possible that one failing barrier will affect following barriers in a negative way. Table 21 shows that there was one occasion when turbidity events in filtrate water and drinking water coincided. However, this is not a good example of a coinciding event as drinking water is limed filtrate water and, hence, elevated value for turbidity in the filtrate water is likely to be detected in the drinking water as well. Nevertheless, it is obvious that coinciding events that affects several parameters in several locations in adjacent time are possible and must be taken into account when assessing the overall risk.

9.2 Further use of the event data

It is at this stage not clear if the identified possibly hazardous events are of significance to health risk. There are still two important general concerns regarding events and their impact:

1. If the event is of short duration does it constitute a major or irrelevant hazard?
2. How long can suboptimal performance be tolerated before risk becomes unacceptable?

Even though the answer to these questions is beyond the scope of this thesis it is a concern for future efficient use of SCADA data. Risk assessment is not an exact science. Even though most of the events are not likely to be of significance to microbial risk, it is still possible to come up with a worst case scenario, assuming that a given deviation equals a total failure of the treatment step. If the result from this indicates that a health effect is at hand, further data can be acquired to undertake further studies of the cause.

By quantifying hazardous events a more accurate picture of the real risks can be achieved. The outcome of annualized risk estimates might substitute for the common way of estimating risk as a combination of likelihood and severity. In this way, uncertainties and value judgements associated with expert assessments of the above factors can be circumvented as the risk estimate is scientifically underpinned throughout QMRA. Even though a lot of uncertainties also are associated with the QMRA process, it provides a theoretically true order of magnitude of the risks (Roser *et al.,* 2005).

The compiled statistics on failure of coagulation, filtration and disinfectant processes has been incorporated as an input in a proposed QMRA modelling simulation in Work Package 6 in Microrisk (Roser *et al.,* 2005). The statistics have been used as a basis for modelled event conditions. The outcome of the risk simulation applied on LWTP shows that events, despite their short duration, has a far greater impact on the annualized risk than the risk originating during baseline conditions. Short term malfunctions in the disinfection may pose a significant health risk whereas malfunctions in coagulation and filtration may not (Roser *et al.,* 2005).

Part three – Conclusion

10 Results

The results of the literature study show that continuous monitoring is a proposed method to improve the risk management process (Cutler, 1997; Scott *et al*, 1999; WHO, 2004). Scott *et al* (1999) reason that as the society in increasing extent tends to put the risks in focus it is likely that regulators and public opinion will demand better quality measurements to prevent or manage the risks. Further, Scott *et al* (1999) states that:

"The current reliance on sampling and laboratory analysis exposes companies to the risk of undetected incidents; suggesting the need for continuous measurement so as to demonstrate diligence"

SCADA systems are, in theory, ideal sources of data for quantitative risk assessment as they can record and store large amount of high resolution data from the process. A lot of sensors can be connected to the system and the data can be displayed the way the user requires (Bailey & Wright, 2003).

However, the literature study also suggests that the use of SCADA data for risk management has several drawbacks. The use of SCADA data is associated with a lot of uncertainties, such as noise. The systems are also complicated and require different operating skills and the operator can not see beyond the sensors (Bailey & Wright, 2003). Furthermore, the conceptual relationship between SCADA data and microbial risk is not always certain.

The results of the case study show that SCADA data time series differ greatly in appearance and hence also in the way they could be analysed and interpreted. It was possible to estimate frequency, duration and magnitude for events as well as statistics for baseline conditions from SCADA data. However, identification and quantification of events and the analysis of corresponding diary records and reports were time demanding if not undertaken in a systematic way.

Most of the identified events were listed in the diary and not in the deviation reports. As shown by the case study, maintenance corresponds to a great part (approximately 60 %) of the identified events. The duration of the identified events, with few exceptions, all ranged between 0.5 and 2.3 hours.

To identify and quantify hazardous events in SCADA data sets, time series analysis was used. From the results of the case study, it is clear that improved time series analysis could prove a range of benefits for risk management.

11 Discussion

SCADA systems are suitable for identifying events in real time. The systems collect high resolution data which allows the process to be followed and enables detection of hazardous events not detected by other methods. The SCADA data appear to be quantitative and detailed in a form that compliments laboratory data. This attribute makes it potentially suitable for use in QMRA.

However, there are some drawbacks associated with the use of SCADA systems. The main question that arises appears to be: how much do SCADA systems actually say about a system? This is likely to be dependent on how the system is used. As shown by Scott *et al* (1999) a lot of SCADA systems do not serve their purpose. SCADA systems generate large amounts of data. As it appears, much of the data is not used for purposes other than alarming function on a day to day basis. It is evident that incorrectly installed and operated SCADA systems may contribute to an overall lack of confidence in these systems.

No single method for interpreting SCADA to identify potentially hazardous events was identified. The different appearance of the SCADA data necessitates different approaches to identify the worst case events. Different ways of identifying and quantifying events has different time demands. Identifying and quantifying the event empirically is more time demanding than identifying and quantifying the events by deviation of given limits which can be undertaken in a systematic way.

Time series analysis could be useful to apply on SCADA data records. There are numerous ways of interpreting time series (Rodionov, 2005). To not overload the operator, time series analysing should be carried out automatically and be incorporated in the SCADA software. As SCADA data series differ in appearance, the use of time series analysis must be explored on a variety of data sets. Different ways of undertaking the analysis must be studied further.

The SCADA systems generate large amounts of data. Even when there is not a storage problem, the large amount of data are difficult to process. For example, 10-minute SCADA data for a year consists of approximately 52 560 records. The upper limit in MS Excel is 65 536 records and the program is not able to show 2D charts consisting of more than 32 000 records. Ideally, alternative software should be used for processing SCADA data. LWTP already uses a system that samples with a higher frequency during deviations, but still saves a sample each minute. To further reduce the size of SCADA data sets, one option might be to process the data and keep high resolution data during periods of deviation and low resolution data during normal (optimal) conditions.

The maintenance equals a common cause of variation and as the aim should be to have a stable process one would like to disregard common causes of variation. Ideally, to create a stable baseline without common cause of variation, SCADA data sampled during cleaning, maintenance or during periods with unrepresentative monitoring should be annotated. Preferably, this could be undertaken by direct crosslink to the electronic diary. By doing this one will be able to better separate the special causes of variation, that is possibly hazardous events.

Overall positive attributes to SCADA:

- SCADA data is a good source from which to identify potential hazardous events that otherwise might have passed without detection
- SCADA systems have the potential for on-line event identification which enables a quick response from the operator when an event is at hand
- SCADA analysis adds knowledge about the system and "knowing your system" is a prerequisite for undertaking assessments of risks
- SCADA analysis generates numerical data suitable for QMRA

Disadvantages with SCADA and how it is used today:

- SCADA systems are not likely to detect all events and should, hence, be seen as complimentary to grab sampling and laboratory tests
- SCADA data does not say everything about your system and can thus lull the management into a false sense of safety
- SCADA analysis is to a great extent dependent on accurate diary records
- The use of SCADA data is associated with a lot of uncertainties:
    - Inherent in the system
        - There are seasonal variations in baseline values that can complicate identification of events
        - Inherent noise can create data with low validity
    - Lack of knowledge
        - The relationships between deviating parameters such as for example turbidity, chlorine residual or pH and microbial risk are not certain or varying
        - Measurement at a meter might not be representative for the main flow or for measuring the actual process performance
    - Technical
        - Poorly calibrated meters could create sets of data with low validity
        - Meters behaving differently makes it risky to compare measurements between different meters
        - Signal translation, processing and storage can affect the appearance of the data
        - Faulty cables can affect the appearance of the data
        - Errors in software can affect the way the process is supervised and controlled

Much more analysis of SCADA data from different water treatment plants should be carried out to develop the use of SCADA data for risk assessment. This initial analysis showed that one value of SCADA data lies in its ability to identify and provide estimates of duration of potential hazardous events. Such a study could be performed at any water treatment plant that has a SCADA and diary system similar to that of LWTP. However, before SCADA data can be used generally to assess risk at water treatment plants, further studies needs to be pursued to facilitate this work. Recommendations coming out from this study are:

- For further research
    - Studies about how different SCADA parameters are relevant to microbial risk should be pursued
    - Studies on the extent of deviation that could contribute to microbial risk should be pursued
    - Studies about where to locate SCADA data measuring points relevant for microbial risk should be pursued
    - Studies about SCADA systems ability for on-line event identification should be pursued on a set of different water treatment plants
    - The use of CUSUM or other statistical process control methods should be further studied on a variety of SCADA data sets from water treatment plants
    - On-line monitoring should be integrated with HACCP
- For management of water treatment plants
    - Diary records with time reference provide useful information for event identification and should be recorded continuously
    - To further reduce the size of SCADA data sets, one option might be to process the data and keep high resolution data during periods of deviation and low resolution data during normal (optimal) conditions
    - SCADA data collected during cleaning, maintenance or during periods with unrepresentative monitoring should be annotated, preferably by direct crosslink to electronic diary

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Appendix A: Abbreviations and glossary

AWTP	Abbreviation for "Alelyckan Water Treatment Plant"
Control Point	NACMCF (1997) defines a control point as: *"A control point (CP) is any step at which biological, chemical, or physical factors can be controlled."*
Critical Control Point	NACMCF (1997) defines a critical control point as: *"A critical control point (CCP) 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."*
Critical Limit	USFDA (2005) defines a critical limit as: *"the maximum or minimum value to which a physical, biological, or chemical parameter must be controlled at a critical control point to prevent, eliminate, or reduce to an acceptable level the occurrence of the identified food safety hazard."*
CUSUM	Abbreviation for "Cumulative Sum Control Charting". A method to undertake change point analysis.
FNU	Abbreviation for "Formazin Nephelometric Unit". It is a measurement of turbidity. FNU data often are not directly comparable to NTU data.
HACCP	Abbreviation for "Hazard Analysis and Critical Control Point". A management tool that identifies, evaluates, and controls hazards that are significant for public health.
Hazard	Nadebaum *et al.* (2004) defines a hazard as: *"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."* This thesis is delimitated to deal with microbial safety. Hence; chemical, physical or radiological agents will not be further examined.
Hazardous event	Nadebaum *et al.* (2004) defines a hazardous event as: *"A hazardous event is an incident or situation that can lead to the presence of a hazard."*
Indirect measurement	An indirect measurement is a measurement that acts as a surrogate for a direct measurement. For example, turbidity can act as surrogate for laboratory sampling to detect pathogens.
LWTP	Abbreviation for "Lackarebäck Water Treatment Plant".
Monitoring	Medema and Smeets (2004) define monitoring as: *"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."*

NTU	Abbreviation for "Nephelometric Turbidity Units". ". It is a measurement of turbidity. NTU data often are not directly comparable to FNU data.
Pathogen	Medema and Smeets (2004) define a pathogen as: *"A pathogen is a micro-organism capable of causing disease."*
PRA	Abbreviation for "Probabilistic Risk Analysis". A methodology that aims to derive an overall probability for the occurrence of a hazard.
Preventive measures	Nadebaum *et al*. (2004) defines preventive measures as: *'Preventive measures are any planned actions, activities or processes used to prevent hazards from occurring or reduce them to acceptable levels*.
Risk	WHO (2005) defines risk as: *"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."*
SCADA	Abbreviation for "Supervisory Control and Data Acquisition". An on-line system that can be used to acquire data from and/or control a process.
WHO	Abbreviation for "World Health Organization".
WSP	Abbreviation for "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	Abbreviation for "Water Treatment Plant".

Appendix B: Turbidity statistics and events

Appendix B - Table 1. Turbidity SCADA data summary

	Raw water	Filtrate water		Drinking water
Time period	01/Oct/2004-19/Sep/2005	01/Oct/2004-19/Sep/2005		01/Oct/2004-19/Sep/2005
Parameter studied	Turbidity raw water	Turbidity filtrate south and north		Turbidity drinking water
Parameter resolution	10 minute	10 minute		10 minute
		North	*South*	
Maximum	1.96	0.54	0.40	1.00
Arithmetic mean	1.01	0.03	0.03	0.04
Minimum	0.73	0.00	0.02	0.02
Standard deviation	0.19	0.01	0.01	0.02
Number of measurements	50975	50975		50975
Alarm range LWTP	<0.01 and >1.80 FNU	<0.01 and >0.40 FNU		<0.01 and >0.20 FNU
Nominal maintenance at LWTP	Meters should (ideally) be cleaned every 2 weeks.	Meters should (ideally) be cleaned every 2 weeks.		Meters should (ideally) be cleaned every 2 weeks.

Appendix B - Table 2. Identified turbidity events in raw water

Event date	Diary/Deviation Report record	Mark	Possible impact on microbial risk
07/Oct/2004	Cleaning of meter	MD	No
28/Oct/2004	-	MP	No
29/Nov/2004	-	MP	No
03/Dec/2004	-	MP	No
06/Dec/2004	-	MP	No
16/Dec/2004	Cleaning of meter	MD	No
09/Jan/2005-10/Jan/2005	-	UK	Yes
01/Feb/2005	Cleaning of meter	MD	No
25/Feb/2005	-	MP	No
15/Mar/2005	-	UK	Yes
22/Mar/2005	Cleaning of meter	MD	No
26/Mar/2005-10/May/2005*	-	UK	Yes
04/Apr/2005	-	UK	Yes
08/Apr/2005	-	MP	No
15/Apr/2005	-	MP	No
27/Apr/2005	Cleaning of meter	MD	No
10/May/2005	-	MP	No
23/May/2005	-	MP	No
26/May/2005	-	MP	No
08/Jun/2005	-	MP	No
10/Jun/2005	Cleaning of meter	MD	No
22/Jun/2005	-	MP	No
11/Jul/2005	-	MP	No
22/Jul/2005	Cleaning of meter	MD	No
17/Aug/2005	-	MP	No
25/Aug/2005	Cleaning of meter	MD	No
02/Sep/2005	-	UK	Yes
09/Sep/2005	-	UK	Yes
16/Sep/2005	-	MP	No

Note:
1. “Possible impact on microbial risk” is a subjective measurement.
2. * = Event detected solely by CUSUM.
3. MD = Maintenance in diary event
4. MP = Maintenance probable event
5. UK = Unknown event

Appendix B - Table 3. Identified turbidity events in filtrate water north

Event date	Diary/Deviation Report record	Mark	Possible impact on microbial risk
08/Oct/2004	Cleaning of meter	MD	No
01/Feb/2005-26/May/2005*	Raw water chlorination stopped 01/Feb/2005-31/May/2005	MD	Yes
03/Feb/2005	-	UK	Yes
10/Feb/2005 08:20	-	UK	Yes
10/Feb/2005 15:40	-	UK	Yes
18/Feb/2005	Cleaning of meter	MD	No
24/Feb/2005 03:40	-	UK	Yes
24/Feb/2005 12:30		UK	Yes
24/Feb/2005 20:10	-	UK	Yes
25/Feb/2005	-	UK	Yes
28/Feb/2005	-	UK	Yes
23/Mar/2005	Shift of filtrate water pump	MD	No
07/Apr/2005	Shift of filtrate water	MD	No
03/May/2005	Cleaning of meter	MD	No
02/Jun/2005	Cleaning of meter	MD	No
28/Jun/2005	-	UK	Yes
04/Sep/2005	-	UK	Yes

Note:
1. "Possible impact on microbial risk" is a subjective measurement.
2. * = Event detected solely by CUSUM.
3. MD = Maintenance in diary event
4. UK = Unknown event

Appendix B - Table 4. Identified turbidity event in filtrate water south

Event date	Diary/Deviation Report record	Mark	Possible impact on microbial risk
08/Oct/2004	Cleaning of meter	MD	No
01/Feb/2005-26/May/2005*	Raw water chlorination stopper 01/Feb/2005-31/May/2005	MD	Yes
18/Feb/2005	Cleaning of meter	MD	No
28/Feb/2005	-	UK	Yes
02/Mar/2005	Shift alum dosing scales	MD	No
15/Mar/2005	Shift alum dosing scales	MD	No
01/Apr/2005	Shift alum dosing scales	MD	No
07/Apr/2005	Shift of filtrate water	MD	No
15/Apr/2005	Shift of alum silo	MD	No
03/May/2005	Cleaning of meter	MD	No
02/Jun/2005	Cleaning of meter	MD	No
21/Jun/2005	No flow filtrate south	MD	No

Note:
1. "Possible impact on microbial risk" is a subjective measurement.
2. * = Event detected solely by CUSUM.
3. MD = Maintenance in diary event
4. UK = Unknown event

Appendix B - Table 5. Identified turbidity events in drinking water

Event date	Diary/Deviation Report record	Mark	Possible impact on microbial risk
08/Oct/2004	Cleaning of meter	MD	No
14/Oct/2004	Shift of drinking water pump	MD	No
29/Oct/2004	Not representative flow	ID	No
23/Nov/2004	Shift of lime pipe	MD	No
30/Nov/2004	Cleaning of meter	MD	No
04/Jan/2005	Shift of drinking water pump	MD	No
27/Jan/2005	Cleaning of meter	MD	No
18/Feb/2005	Cleaning of meter	MD	No
24/Feb/2005	Shift of lime pipe	MD	No
16/Mar/2005	Shift of drinking water pump	MD	No
07/Apr/2005	Shift of drinking water pump	MD	No
30/Apr/2005	Drinking water pump stopped due to electric current break	ID	No
03/May/2005	Shift of drinking water pump	MD	No
02/Jun/2005	-	UK	Yes
28/Jun/2005	-	UK	Yes
09/Jul/2005	Drinking water pump stopped due to electric current break	ID	No
30/Aug/2005	Cleaning of meter	MD	No

Note:
1. "Possible impact on microbial risk" is a subjective measurement.
2. MD = Maintenance in diary event
3. ID = Incident in diary event
4. UK = Unknown event

Appendix C: Chlorine residual statistics and events

Appendix C - Table 1. Chlorine residual SCADA data summary

	Raw water weir	Drinking water
Time period	01/Oct/2004-19/Oct/2004 and 13/Jan/2005-19/Sep/2005	01/Oct/2004-19/Sep/2005
Parameter studied	Chlorine residual raw water weir	Chlorine residual drinking water
Parameter resolution	10 minute	10 minute
Maximum	0.30 mg/L	0.44 mg/L
Arithmetic mean	0.06 mg/L	0.20 mg/L
Minimum	0.00 mg/L	0.00 mg/L
Standard deviation	0.04 mg/L	0.04 mg/L
Number of measurements	38819	50975
Alarm range LWTP	<0.04 and >0.20 mg/L	<0.12 and >0.38 mg/L
Nominal maintenance at LWTP	Every 4 week or at deviation from lab value (tolerance 0.02 units)	Every 4 week or at deviation from lab value (tolerance 0.02 units)

Appendix C - Table 2. Identified chlorine residual events in raw water weir

Event date	Diary/Deviation Report record	Mark	Possible impact on microbial risk
15/Oct/2004	-	UK	Yes
19/Oct/2004*	Raw water chlorination stopped due to water temperature < 12 degrees Celsius	MD	No
13/Jan/2005*	Raw water chlorination started	MD	No
23/Mar/2005*	Raw water chlorination dose adjusted	MD	No
31/May/2005*	Raw water chlorination dose adjusted	MD	No
09/Jul/2005	Power cut	ID	No
11/Jul/2005	-	UK	Yes
15/Jul/2005	Power cut	ID	No
16/Jul/2005	-	UK	Yes
13/Aug/2005	DEVIATION: Low chlorine dosing LWTP	IR	Yes
27/Aug/2005	-	UK	Yes
19/Sep/2005	Flow stopped to meter	ID	No

Note:
1. "Possible impact on microbial risk" is a subjective measurement.
2. * = Event detected solely by CUSUM.
3. UK = Unknown event
4. MD = Maintenance in diary event
5. ID = Incident in diary event
6. IR = Incident in report event

Appendix C - Table 3. Identified chlorine residual events in drinking water

Event date	Diary record	Mark	Possible impact on microbial risk
25/Oct/2004	Drinking water pump stopped due to power cut	ID	No
08/Jan/2005 17:50	Drinking water pump stopped due to power cut	ID	No
08/Jan/2005 20:00	Drinking water pump stopped due to power cut	ID	No
30/Apr/2005	Drinking water pump stopped due to power cut	ID	No
09/Jul/2005	Drinking water pump stopped due to power cut	ID	No
15/Jul/2005	Drinking water pump stopped due to power cut	ID	No
17/Aug/2005	Cleaning of meter	MD	No
09/Sep/2005	-	UK	Yes

Note:
1. "Possible impact on microbial risk" is a subjective measurement.
2. ID = Incident in diary event
3. MD = Maintenance in diary event
4. UK = Unknown event

Appendix D: pH statistics and events

Appendix D - Table 1. pH SCADA data summary

	Flocculation in	
Time period	01/Oct/2004-19/Sep/2005	
Parameter studied	pH	
Parameter resolution	10 minute	
	North	*South*
Maximum	6.97	6.97
Arithmetic mean	6.53	6.50
Minimum	5.96	5.94
Standard deviation	0.05	0.05
Counts	50975	50975
Alarm range LWTP	<5.90 and >6.95	
Nominal maintenance at LWTP	Every 2 weeks	

Appendix D - Table 2. Identified pH events in flocculation chamber one north

Event date	Diary/Deviation Report record	Mark	Possible impact on microbial risk
20/Jan/2005	DEVIATION: Deviation due to wrong displayed raw water flow in computer Lackarebäck	IR	Yes
03/Feb/2005	Increased NaOH dosing	MD	No
07/Feb/2005	Testing raw water NaOH dosing pump	MD	No
10/Feb/2005	Problems with alum scale	MD	No
27/Feb/2005 11:20	Turbine started causing severe deviation in raw water flow	ID	Yes
02/Mar/2005	Shift of alum scale	MD	No
27/Jul/2005	Shift of alum scale	MD	No
07/Sep/2005	Shift of alum scale	MD	No

Note:
1. “Possible impact on microbial risk” is a subjective measurement.
2. IR = Incident in report event
3. MD = Maintenance in diary event
4. ID = Incident in diary event

Appendix D - Table 3. Identified pH events in flocculation chamber one south

Event date	Diary/Deviation Report record	Mark	Possible impact on microbial risk
22/Dec/2004	-	UK	Yes
20/Jan/2005	DEVIATION: Deviation due to wrong displayed raw water flow in computer Lackarebäck	IR	Yes
27/Jan/2005	Increased NaOH dosing	MD	No
02/Feb/2005	Decreased NaOH dosing	MD	No
03/Feb/2005	Increased NaOH dosing	MD	No
07/Feb/2005	Testing raw water NaOH dosing pump	MD	No
10/Feb/2005	Problems with alum scale	MD	No
27/Feb/2005 06:40	Turbine stopped causing severe deviation in raw water flow	ID	Yes
27/Feb/2005 11:20	Turbine started causing severe deviation in raw water flow	ID	Yes
02/Mar/2005	Shift of alum scale	MD	No
13/Apr/2005	Shift of alum scale	MD	No
11/May/2005	Shift of alum scale	MD	No
10/Jun/2005	Problem with fuse	ID	No
21/Jun/2005	Production line south shut off	MD	No
07/Sep/2005	Shift of alum scale	MD	No

Note:
1. "Possible impact on microbial risk" is a subjective measurement.
2. UK = Unknown event
3. IR = Incident in report event
4. MD = Maintenance in diary event
5. ID = Incident in diary event

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