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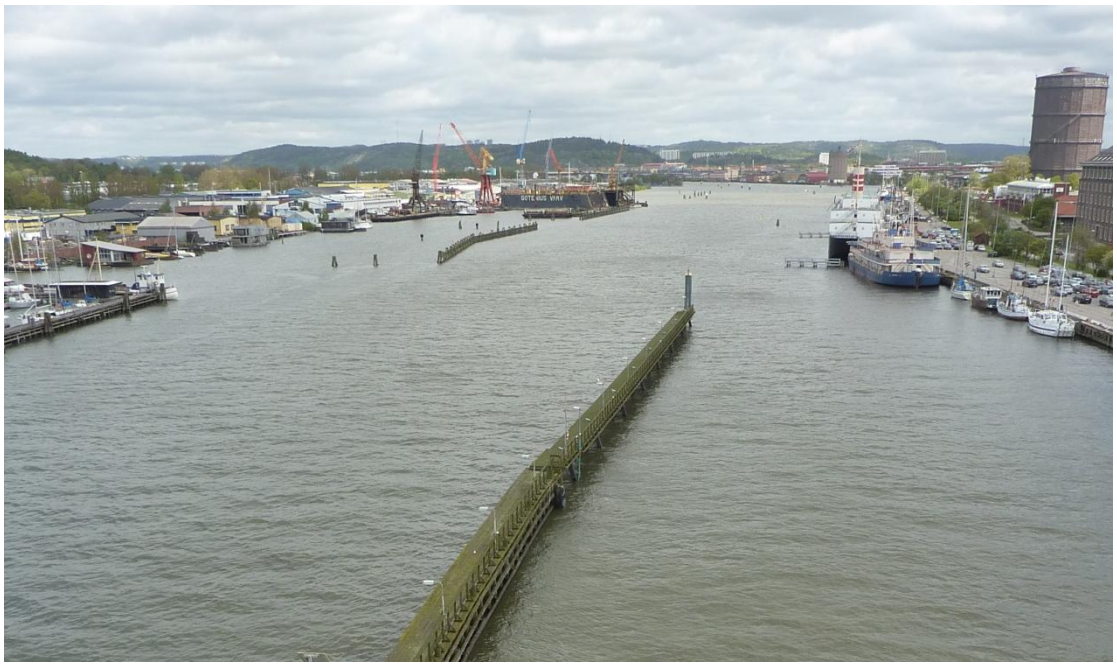

Disc Filters to Reduce Wastewater Pathogen Levels in Raw Water Sources

Risk Reduction Potential for Göta älv

Master of Science Thesis in the Master's Programme Geo and Water Engineering

CHRISTINE ENERHALL & EMMA STENMARK

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Cover:
View of Göta älv from Göta älvsbron. Photo: Emma Stenmark

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ABSTRACT

Recent studies have indicated that municipal wastewater treatment plants (WWTPs) are more or less insufficient in removing pathogens and that treated wastewater effluent is a major source of microbiological contaminants to surface waters. As many surface waters act as raw water sources, one important step in securing safe drinking water is to improve wastewater treatment regarding microbiological contaminants. Disc filters have showed potential to reduce pathogens if installed as a treatment step in municipal WWTPs, though, the knowledge is limited. This study aimed to further investigate to what degree disc filters could decrease the pathogen levels in raw water sources by assessing the removal efficiency through field measurements at the up and running disc filter facility at Rya WWTP. Concentrations of indicator organisms as well as *Norovirus* were measured in the influent and in the effluent, both over individual filters and over the whole facility. The calculated removal efficiencies were connected to large uncertainties. However, it could be concluded that disc filters as a tertiary treatment step at WWTPs showed some removal of indicator, which indicate removal of pathogens as well. Analysis of *Norovirus* though showed negative removal efficiency. In general the removal efficiencies were to be considered quite low in comparison to other options for tertiary treatment. Installing disc filters to reduce the microbiological risk only is therefore not defendable. A risk assessment was then performed on Göta älv to evaluate the risk reduction potential of installation of disc filters at all WWTPs. This included an inventory of the WWTPs along Göta älv and of Alelyckan drinking water treatment plant (WTP). The risk reduction potential was quantified as decrease of indicator organism/pathogen concentration at Lärjeholm raw water intake as well as decrease in disease cases among the drinking water consumers in Göteborg municipality. From the risk assessment it was possible to conclude that installation of disc filters in general would lower the base concentration in the river and consequently to some degree lower the risks for drinking water consumers in Göteborg municipality. However, installation of disc filters cannot alone lower the highest peak concentrations to meet the guideline values for raw water. Other measures are necessary to control these peak concentrations and lower the risks to an acceptable level.

Key words: Disc filter, Wastewater treatment, Removal efficiency, Faecal indicator organisms, *Cryptosporidium*, *Norovirus*, Risk assessment, Raw water protection

Skivfilter för att minska halter av patogener från avloppsvatten i råvattentäkter
Riskminskningspotential för Göta älv
Examensarbete inom Geo and Water Engineering
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SAMMANFATTNING

Nyligen gjorda studier har indikerat att kommunala avloppsreningsverk har mer eller mindre otillräcklig rening av patogener samt att renat avloppsvatten är en stort bidragande källa till mikrobiologiska föroreningar i ytvatten. Då många ytvatten används som råvattenkällor är ett viktigt steg i att trygga en säker dricksvattenkvalité att förbättra avloppsvattenreningen av patogener. Skivfilter har visat potential gällande att reducera patogener då de är installerande som tertiärt reningssteg i avloppsreningsverken, dock är kunskapen begränsad. Den här studien syftar till att utreda i vilken grad skivfilter kan reducera patogennivåerna i råvattentäkter genom att undersöka reningseffektiviteten genom fältundersökningar i skivfilteranläggningen på Rya WWTP. Koncentrationer av fekala indikatororganismer samt *Norovirus* mättes i inflöde och utflöde, både över enskilda filter och över hela anläggningen. De beräknade avskiljningseffektiviteterna var förknippade med stora osäkerheter. Dock kunde utläsas att skivfilter hade viss reningsförmåga av indikatororganismer vilket i sin tur indikerar viss förmåga att rena vissa patogener. För *Norovirus* påvisades negativ avskiljningseffektivitet. Generellt kan sägas att avskiljningseffektiviteten anses låg jämfört med andra alternativ för tertiär rening.Därför kan det inte anses försvarbart att installera skivfilter enbart för att minska den mickrobiologiska risken. En riskutvärdering utfördes därför för Göta älv för att utvärdera potentialen att använda skivfilter för råvattenskydd. Detta inkluderade en inventering av avloppsreningsverken längs Göta älv och av Alelyckan vattenverk. Riskminskningspotentialen kvantifierades som minskningen av indikator organism/*Norovirus* koncentrationer vid Lärjeholm råvattenintag samt som minskningen av sjukdomsfall hos dricksvattenkonsumenterna i Göteborg kommun. Från riskbedömningen kunde konstateras att installation av skivfilter generellt skulle sänka baskoncentrationen av patogena mikroorganismer och därmed även minska riskerna för dricksvattenkonsumenterna i Göteborgs kommun. Installation av skivfilter skulle dock ej ensamt minska toppkoncentrationerna så att riktlinjerna för råvattnet möts. Ytterligare åtgärder är nödvändiga för att sänka dessa toppkoncentrationer samt för att sänka risken till en acceptabel nivå.

Nyckelord: Skivfilter, Avloppsvattenrening, Reningseffektivitet, Fekala indikatorbakterier, *Cryptosporidium*, *Norovirus*, Riskbedömning, Råvattenskydd

Contents

Preface

In this study, the removal efficiency of pathogens of disc filters has been investigated in order to evaluate installing disc filter in wastewater treatment plants as a risk reducing option for raw water sources. The removal efficiency was studied through a measurement campaign carried out during the spring 2012 at Rya wastewater treatment plant. The project was carried out at the Department of Civil and Environmental Engineering, the Division of Water Environment Technology, Chalmers University of Technology, Sweden. The project is partly financed by the DRICKS research programme and by the Division of Water Environment Technology at Chalmers University of Technology.

The study has been carried out with Assistant Professor Thomas Pettersson as supervisor. The measurement campaign at Rya WWTP was performed with much appreciated help from Gryaab. Especially thanks to Pierre Lindqvist, without his assistance the sampling would not have been possible. We are also grateful towards the EU research project VISK for contributing with the analysis of *Norovirus* and for providing measurement data. The personnel at Lackarebäck laboratory in Göteborg and at Länssjukhuset Ryhov laboratory in Jönköping should be acknowledged for carrying out the analyses. We would also like to thank Associate Professor Britt-Marie Wilén for the help with the particle distribution analysis as well as her general guidance and support.

Finally, we are grateful to Trollhättan Energi and Andreas Tengklint for their co-operation.

Göteborg June 2012

Christine Enerhall & Emma Stenmark

Notations and Acronyms

Notations:

$C_{effluentWWTP}$	Concentration of indicator organisms/pathogens in the wastewater effluent
C_{inlet}	Concentration of indicator organisms/*Norovirus* before disc filters/disc filter facility
$C_{Lärjeholm}$	Concentration at Lärjeholm raw water intake
C_{outlet}	Concentration after disc filters/disc filter facility
$F_{effluentWWTP}$	Outflow from the wastewater treatment plants
$F_{Götaälv}$	Flow in Göta älv
R	Removal efficiency

Acronyms:

BOD	Biological Oxygen Demand
cfu	Colony-forming units
DALYs	Disability Adjusted Life Years
DLVO	Derjaguin-Landau-Verwey-Overbeek
EHEC	*Enterohaemorrhagic E. coli*
EIEC	*Enteroinvasive E. coli*
EPEC	*Enteropathogenic E. coli*
ETEC	*Enterotoxigenic E. coli*
GDP	God Desinfektions Praxis
HACCP	Hazard Analysis and Critical Control Point
MPC	Most Probable Concentration
MRA	Swedish Microbiological Risk Assessment
N_{tot}	Total nitrogen
PCR	Polymerase Chain Reaction
PD	Post Denitrification
pe	Person equivalent
pfu	Plague-forming units
P_{tot}	Total phosphorous
QMRA	Quantitative Microbial Risk Assessment
Spp	Species
SS	Secondary Sedimentation
VISK	Virus i Vatten – Skandinavisk Kunskapsbank
WSP	Water Safety Plan
WTP	Drinking Water Treatment Plant
WWTP	Wastewater Treatment Plant

1 Introduction

Being able to provide drinking water of good quality is of great concern for the drinking water producers to avoid large outbreaks of intestinal disease among the consumers. In fact, according to Swedish law the drinking water producers are obliged to ensure that the water supplied is safe and existing drinking water regulations are followed (Livsmedelsverket, 2011).

The traditional approach to manage the requirements is through drinking water treatment. Drinking water treatment plants (WTPs) use microbiological barriers to remove pathogenic microorganisms like bacteria, virus and protozoa by either deactivation or separation. However, diverse effectiveness for different pathogens in different treatment steps and shortcomings in process optimization and operation makes it very hard to ensure efficient treatment during all times (WHO, 2008).

Adding to the problem of ensuring efficient treatment in the WTP during all times is the diversity of pathogen sources creating varying pathogen concentrations in the raw water. There is a baseline input of pathogens from everyday events and on top of this are inputs from accident and weather related events. One important source is the effluents from municipal wastewater treatment plant as even a fully functioning treatment process seldom manage to efficiently remove the high pathogen concentrations in raw sewage (OCED & WHO, 2003). Other main sources of pathogens are faecal discharges from on-site septic systems and private sewers, wastewater overflows and runoff from farmlands and pasturelands. A major risk event in drinking water supply is peak precipitation. Runoff may wash large quantities of faecal matter to receiving raw water sources. The precipitation could also cause overflows at wastewater treatment plants (WWTPs), releasing large amount of untreated wastewater containing high quantities of pathogens into the water sources. This causes temporary peak concentrations of pathogens in the raw water sources that could exceed treatment capacity of the barriers at WTP and result in pathogens breaking through the treatment plant and reaching the consumers.

The World Health Organisation (WHO, 2008) declared that ingestion of water contaminated with pathogens is the greatest microbial risk to human health. In Sweden up to 80 % of the reported cases of waterborne infections are due to contaminated raw water where pathogens are not sufficiently removed in the water treatment process (Lindberg & Lindqvist, 2005). Between 1 and 13 outbreaks of waterborne infections have been reported annually and in average almost 1000 individuals are affected every year. This means an annually risk of getting affected by waterborne diseases in Sweden of approximately 1/10000. Sweden has no health target for number of diseases caused by microorganisms. However, according to the United States Environmental Protection Agency (U.S. EPA) the target should be that no more than one of ten thousand people gets affected by waterborne diseases every year (Macier & Regli, 1992), which would put Sweden on the limit in meeting the target.

Due to the uncertainties in the drinking water treatment the preferred strategy to reduce the risk of waterborne infections is, according to WHO (2008), to reduce or prevent pathogens from entering the raw water source in the first place. This is also the approach which has been taken within this study; to control pathogen discharges as a method for risk reduction for raw water sources and reduce the reliance on the drinking water treatment processes for safe drinking water supply.

1.1 Background

The conventional WWTPs operating in Sweden today were mainly constructed during the 1960's and 1970's (NE, 2012). The main problem that challenged the society during that time was eutrophication, which resulted in treatment plants primary designed to remove biological oxygen demanding compounds and nutrients. At that point, minimal focus was dedicated to the removal of pathogenic microorganisms, which actually was the problem that initially set off the need for treatment of wastewater in the mid-20th century.

Although the conventional WWTPs are reducing the number of pathogenic microorganisms, the removal efficiency varies widely between different treatment processes. It is today well known that most conventional WWTPs release more or less pathogenic microorganisms to receiving natural waters. A recent study by Åström and Pettersson (2009) within the DRICKS research programme at Chalmers University of Technology has indicated that treated wastewater effluent is the major source of microbiological contaminants for the river Göta älv. This fact call for attention to the importance of improving wastewater treatment as a step in securing safe drinking water, since many receiving waters also serves as raw water sources.

One important task is to find ways to decrease pathogen levels in the wastewater effluent from the WWTPs by identifying efficient treatment steps for pathogens. As many conventional wastewater treatment plants releases high numbers of microorganisms, the use of effective tertiary treatment methods for the secondary effluent could be a solution to improve the microbial quality in order to protect human health. A unpublished pre-study carried out at Chalmers showed that disc filters could reduce pathogens to some extent, if installed as a treatment step in municipal WWTPs.

River Göta älv and Lake Vänern have been pointed out as the most affected water systems in Sweden with regard to pathogenic microorganisms and it is affirmed that the most common reason for closing the raw water intake at Lärjeholm in Göteborg is due to high levels of bacteria (Göta Älvs Vattenvårdsförbund, 2007a). This makes Göta älv a particular interesting object to study when looking at preventive measures for microbiological pathogen contamination.

1.2 Aim and goal

The aim of this report is to investigate to what degree disc filters could decrease the risk of high pathogen levels in raw water sources by assessing the removal efficiency of pathogens of disc filters through field measurements at a WWTP. The goal is to evaluate the risk reduction potential of disc filter installations at wastewater treatment plants in order to protect raw water sources.

The report will present an analysis of how much pathogens in Göta älv can be decreased by installation of disc filters at all wastewater treatment plants with discharge into the river and how big the risk reduction potential is for the consumers in Göteborg municipality.

The following questions will be answered in this report:

- *What is the pathogen removal efficiency of disc filters?*
- *Does installation of disc filters at all wastewater treatment plants along River Göta älv have potential to reduce the risk of high pathogen levels in the raw water source and in the long run reduce the risk of disease outbreaks among the consumers in Göteborg municipality?*
- *What general conclusions can be drawn about the risk reduction potential of using disc filters for raw water source protection?*

1.3 Limitations

Due to time and cost limitations the measurement campaign were performed only for one type of disc filters at Rya WWTP in Göteborg with a filter pore size of 15 µm. The measurement campaign was carried out during a limited period of time. Seasonal variations in wastewater properties and weather conditions was therefore not investigated but included in discussion. The removal efficiency was only investigated for a few different types of microbial indicator organisms and pathogens.

The investigation focuses only on the effluents of the municipality wastewater treatment plants along Göta älv under normal operation. Other sources of pathogen contamination and abnormal operation, for instance combined sewer overflow events, were not considered. Neither were other risks related to wastewater effluents than pathogens considered. Calculations of the risk reduction potential from installing disc filters were performed for the raw water intake Lärjeholm in the municipality of Göteborg. The results were then used for estimating the risk reduction potential in general.

2 Literature Review

This chapter presents an introduction to subjects within the areas of raw water protection and drinking water safety as well as waterborne microorganisms and microbial removal in different wastewater treatment systems. The intention is to give the reader sufficient background to understand the results of the investigation.

2.1 Raw water protection and drinking water safety

As mentioned, the traditional approach to manage risks concerning pathogens in drinking water is through treatment of the raw water before distribution. The Swedish National Food Administration states that WTP should have enough barriers to ensure safe drinking water (Livsmedelsverket, 2011). For a drinking water treatment plant to be considered as safe in Sweden, multiple microbiological barriers should be used (Lindhe, 2010). A barrier in this context is a physical barrier in the treatment process at the drinking water plant. Common barriers are chemical precipitation followed by filtration and disinfection by chlorination, UV radiation and/or ozonation. However, it is important to embrace the fact that a safe treatment process on its own is not enough to ensure a sufficient quality at all times of the drinking water distributed to the consumers.

WHO guidelines (2008) states the most effective way to ensure a safe drinking water supply is to implement risk assessment and risk management that includes all steps in the drinking water system, from catchment to consumer. Their suggested approach is to use a Water Safety Plan (WSP) to assess the risk. This is quite an extensive process and it is described as a three component procedure. The first step is to carry out an extensive hazard assessment, followed by a risk control classification and finally development of a management plan for standard and non-standard conditions.

Today neither the Swedish nor the European legislation require a WSP. However, Svenskt Vatten (2012b) suggests a similar method for protection of drinking water from microbial contamination, also including the whole pathway between raw water and consumer. This includes identifying and monitoring variations of the quality of the raw water regarding pathogenic microorganisms and to be able to adjust the treatment processes to ensure a stable drinking water quality (Svenskt Vatten, 2008). Important steps are microbial contamination evaluation, ensuring sufficient number of barriers as well as to have good knowledge about the raw water.

The way to deal with the risks concerning raw water quality in Sweden partly involves work with water protection areas. The majority of the surface raw water intakes in Sweden have water protection areas established today (Miljöförvaltningen, 2012). Within the protection areas, special safety regulations apply with the purpose to decrease the probability of an accident and to decrease consequences in case of an accident. A part in the process of the establishment of a water protection area is to carry out a risk assessment, which among other risks should include a microbial contamination evaluation. Since January 1st 2012 the legislation also requires the municipal WTPs to implement Hazard Analysis and Critical Control Point (HACCP) in their work. HACCP is a system which identifies, evaluates and controls critical hazards within drinking water, including raw water protection. (Svenskt Vatten, 2012a).

Another approach for raw water protection is to improve the natural water quality by implementing preventive measures. This is measures which prevent or decrease loadings of microbial or other contaminants to water sources. Preventative measures to lower discharge of faecal contaminants could include restrictions of pasture lands atwater sources, limiting combined sewer overflows by separating wastewater systems and establish overflow basins etc. Another important measure is to improve the quality of WWTP effluent. This study focuses on latter and the possibility to use disc filters as a preventative measure.

Surface waters are also used for recreational purposes. When bathing the risk for ingestion of water is high, therefore making it important to protect the water from faecal contamination also for this purpose. The current legislation in Sweden concerning guideline values for both raw water purposes and recreational purposes are discussed below. What could be regarded as acceptable risk for human health from ingestion of drinking water is also discussed.

2.1.1 Guideline values for surface raw water sources

Current source water regulations in Sweden are governed by the European Water Framework Directive (2000/60/EG). The framework does not comprise any guideline values for raw water quality, neither limits nor target values. Instead it covers general ideas concerning the importance of a good raw water quality. The original thought was to implement new raw water requirements into the framework after the pre-existing European Raw Water Directive (75/440/EEC) expired in 2007, but this has still not been realized(Friberg *et al*., 2010).

The Swedish national drinking water regulation, based on the European framework directive, came into force in Sweden in December 2003. At the same time the national guideline values for surface raw water quality, which were based upon the European Raw Water Directive, were taken out of use. However, sometimes the old guideline values are still used as it is difficult to put demand on the water quality without guideline values. In Table 1 these target values concerning concentration of *Escherichia coli* (*E. coli*), total coliforms and enterococci are presented. For specific pathogens the guideline is that the water should not be used if they are detected (Svenskt Vatten, 2008).

Regarding guidelines for water sources used for bathing purposes, the water quality is controlled by the EU bathing water directive (2006/7/EG). The target value for *E. coli* is 500 cfu/100 ml and for enterococci 200 cfu/100 ml for the denotation "Excellent quality" (Friberg *et al*., 2010).

Table 1 *Guideline values for surface raw water for total coliforms, E. coli and enterococci. (cfu = colony forming units) (Svenskt Vatten, 2008)*

Parameter	Unit	Target value
Total Coliforms	cfu/100 ml	<5000
E. coli	cfu/100 ml	<500
Enterococci	cfu/100 ml	<500

2.1.2 Acceptable health risk targets

It is hard to determine what acceptable microbial risk is. Sweden has no health target for maximum number of infected people from waterborne diseases but health targets of some sort are used in some countries and internationally. For example, the U.S. EPA have used a target of 1 infection per 10 000 persons per year from drinking water consumption. However, this target is difficult to follow up since not all who are infected show symptoms.

The WHO often uses the unit DALYs (Disability Adjusted Life Years), which expresses the number of years lost due to disease, to evaluate public health and to assess the disease burden associated with microbial hazards (WHO, 2011). WHO has set the tolerable risk of disease (infections with symptoms) caused by either waterborne chemicals or microbial contaminants to $1 \cdot 10^{-6}$ DALYS per person per year. The health outcome target of $1 \cdot 10^{-6}$ DALYS is typically equivalent to concentrations of pathogens of less than 1 organism per 10^{4}-10^{5} litres of drinking water. As this is very difficult to monitor, water quality targets are typically not developed for pathogens. Instead targets are more often set for indicator organisms in raw water, which are microorganisms that normally exist in the human intestines without causing disease.

2.2 Waterborne microorganisms

Microorganisms are organisms which are too small to be detected by the human eye without any aid, e.g. a microscope. They are ubiquitous, exist in different environments and are diverse in characteristics, behaviour and resistance. (Maier *et al*., 2000). Waterborne microorganisms, which could be found in wastewater and surface waters, include bacteria, fungi, algae, protozoa and viruses (Metcalf & Eddy, 2004). Most microorganisms pose no harm to human health and hundreds of strains exist naturally in large amounts in the human intestines (Stenström, 1996). However, some microorganisms are pathogenic and can cause intestinal and other infectious diseases.

The purpose of this section is to briefly present different types of waterborne pathogenic microorganisms found in wastewater and in Göta älv. It will also be explained how some microorganisms can be used as indicator organisms of faecal contamination. How removal of microorganisms is possible in different treatment processes including disc filtration is described in Section 2.3.

2.2.1 Pathogenic microorganisms in wastewater

Pathogens found in wastewater can be classified into four main categories; bacteria, viruses, protozoa and helminths (Metcalf & Eddy, 2004). In municipal wastewater it is reasonable to assume that the pathogens mainly originate from humans faeces. As human faeces contain large quantities of microorganisms (Stenström, 1996), the wastewater contains large amounts of various microorganisms as well. Studies of the microbial content in wastewater systems in urban areas have shown that also pathogenic microorganisms occur on a more or less continuous basis in wastewater (OECD & WHO, 2003).

The spreading of waterborne pathogen infections and disease profiles in Sweden are described below. The different pathogenic groups are also described with focus on the size and shape of the pathogens rather than on disinfection properties since the removal process in disc filters is of main interest for this report. The selection of pathogens described includes the pathogens most critical for drinking water protection. It is based on WHO's identification of which pathogens have confirmed drinking water relevance in general as well as which pathogens that have been identified as most relevant in Sweden by the Swedish Institute for Communicable Disease Control (SMI).

2.2.1.1 Spread of infection

Pathogens entering the drinking water system can potentially cause large disease outbreaks. The main route for pathogen infection is ingestion of drinking water contaminated with human or animal faeces (the faecal-oral route). However, microbiological drinking-water safety is not related only to faecal contamination as for example some pathogens may grow in water distribution systems (WHO, 2011). Also, spreading by water is many times inferior to other pathways for transmission, including person-to-person contact, by food processing equipment, by inhalation of dust or aerosols and dermal or eye contact (Stenström, 1996). Some pathogens may be transmitted by multiple pathways. The route of interest in this study is though the faecal-oral route with transmission pathway from human faeces, via wastewater and WWTPs to raw water sources and exposure through ingestion of drinking water, see Figure 1.

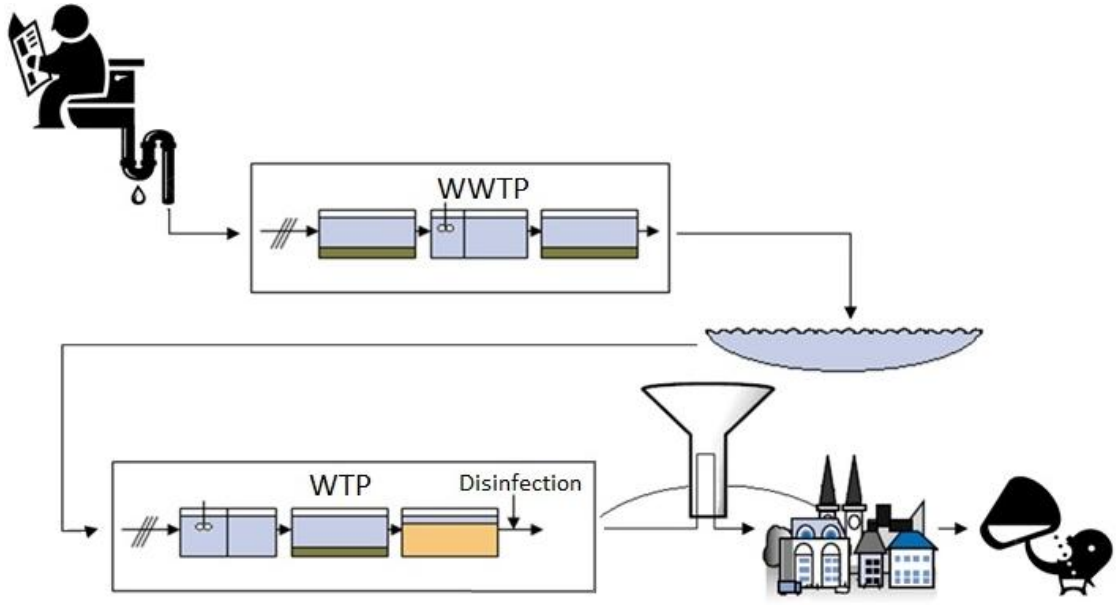

Figure 1 *The faecal-oral transmission pathway of interest in this study.*

In common for pathogens transmitted by the faecal-oral route is that they are excreted in large amounts from faeces by infected people and animals. As the pathogens are excreted from the body there is an immediate reduction partly due to inactivation and partly due to the dilution with the flushing water. (Stenström, 1996) The wastewater is normally collected in wastewater pipe systems to the WWTPs where the inactivation

of pathogens is continued. However, as wastewater treatment processes often have inadequate treatment with regard to pathogens, pathogens consequently are released to receiving waters through the discharge of the wastewater effluent. Typical concentrations of some common pathogens and indicator organisms in international raw wastewater and Swedish raw wastewater effluent respectively are shown in Table 2. These values could however vary significantly between different treatment facilities.

Table 2 *Typical concentrations of pathogens and indicator organisms in untreated wastewater as well as approximate infection doses and relative infectivity.*

Microorganism		Raw wastewater (numbers/litre)	Swedish raw wastewater (numbers/litre)	Infection Dose (c)	Relative infectivity
Bacteria	*Salmonella spp.*	-	10^{4}-10^{7} [c]	10^{2}-10^{4}	-
	Shigella spp.	-	10^{1}-10^{2} [c]	-	-
	Campylobacter	$4 \cdot 10^{4}$ [a]	10^{2}-10^{6} [c]	-	Moderate [d]
Viruses	Enteroviruses	-	-	10^{1}-10^{2}	High [d]
	Norovirus	$10^{3.3}$ [a]	10^{1} [c]	10^{1}-10^{3}	High [d]
	Rotavirus	-	-	10^{1}-10^{3}	-
Protozoa	*Cryptosporidium spp.*	$10^{1.3}$ [a]	10^{1} [c]	10^{3}-10^{4}	High [d]
	Giardia spp.	$10^{3.3}$ [a]	10^{1}-10^{2} [c]	$5 \cdot 10^{3}$-$5 \cdot 10^{4}$	High [d]
Indicator organism	Coliform	10^{8} [b]	-	-	-
	Thermotolerant coliforms/*E. coli*	$3 \cdot 10^{7}$ [b]	10^{6}-10^{8} [c] *	(5-50 for *) d	High [d] *
	Enterococci	$4 \cdot 10^{6}$ [b]	-	-	-
	Clostridium Perfringens	-	-	-	-

[a] Stenström (1996)
[b] Wilen *et al*. (2012)
[c] Bitton (1999)
[d] Pond *et al*. (2004)
*Pathogenic strains (e.g. EHEC)

Once in the receiving water, an important characteristic for waterborne pathogenic microorganisms is that they will be further spread by the water flow (WHO, 2008). This process is further described in Section 2.2.3. The water transport means that the

discharged pathogens can reach raw water intakes and enter the drinking water system.

For a disease outbreak to occur, adequate quantities of pathogens need to enter the body. This is defined as the infection dose and varies between different species. Differences between humans, for example age, general health, disease record, vaccinations and gastric acid production also affect the infection dose. Approximate infection dose for some pathogens can be seen in Table 2. Virus and protozoa often have a low infection dose of 1-20 organisms whereas the infection dose for bacteria has a wide range between 10^2-10^9 organisms (Stenström, 1996). When an infection is established, pathogens multiply in the new host and large amounts are once again excreted with the faeces.

2.2.1.2 Disease picture in Sweden

Disease manifestation and incubation time after infection also depends on both the pathogen specie and the infected individual (Stenström, 1996). Common symptoms are diarrhea, dehydration, stomach ache, fever, nausea and vomiting (Metcalf & Eddy, 2004). Some pathogen can cause more serious symptoms, like respiratory ill-health, brain fever or myocarditis (Stenström, 1996). Moreover, sometimes different types of pathogens are present at the same time giving different symptoms (SMI, 2011a). Some humans carry pathogen without showing any symptoms at all.

Many pathogens causing waterborne infections are compulsory for the health authorities to report and further investigate the cause and infection route (SMI, 2010acde; SMI, 2011bc; SMI, 2012a). In Sweden there have been 1-13 outbreaks of waterborne infections reported annually with between 100 and 13 574 people affected (Lindberg & Lindqvist, 2005). A total of 142 outbreaks with totally 63 000 diseased people were reported between 1980 and 2004 (SMI, 2011a). Still, reported disease cases due to waterborne pathogens seem to be seriously under reported. Different literature suggests that the actual disease cases are 20-200 times larger than reported (Lindberg & Lindqvist, 2005). Considering the difficulty in identifying sporadic disease outbreaks, this number is challenging to determine and it could be even higher. In the largest waterborne outbreak reported in Sweden approximately 27000 people in Östersund were infected with *Cryptosporidium* in November 2010 according to a questionnaire on the municipal homepage (SMI, 2012a). However, only 186 cases were reported to the Swedish Institute for Communicable Disease Control. In spring 2011 a similar outbreak occurred in Skellefeå with approximately 20000 infected, also this outbreak seriously underreported.

In the majority of waterborne outbreaks the causative pathogen has not been possible to identify. This is not surprisingly since there are a large variety of microorganisms which could cause diseases among humans. The majority of reported outbreaks in Sweden, where the pathogen has been identified, have been caused by *Campylobacter* species (spp.), *Norovirus* or *Giardia lamblia*. *Cryptosporidium* has caused the largest outbreak. Pathogenic *Escherichia coli*, *Entamoeba histolyica*, *Salmonella* spp. and *Shigella* spp. have also been identified in connection to outbreaks. Other microorganisms which could cause diseases in Sweden are *Yersinia enterocolitica, Aeromonas hydrophila,* hepatitis A, rota-, coxsackie- and echovirus. (SMI, 2011a) The number of pathogens, for which water is a known transmission pathway, continues to increase as new pathogens continue to be discovered (WHO, 2011).

2.2.1.3 Consequences of an outbreak

The consequences of waterborne infections could be huge. The individuals will, except from the discomfort of being ill, also suffer from partial loss of income. Moreover, if for example 20-90 % of the drinking water consumers to a larger WWTP get infected and have to stay home from work it would cause great financial cost for the society. It is possible to evaluate the cost of this in monetary terms (Lindberg & Lindqvist, 2005). In Milwaukee, for example, a waterborne *Cryptosporidium* outbreak caused 403 000 disease cases, including 4400 people hospitalized, and 69 deaths. The cost of this outbreak was estimated to 96.2 million dollar, of which 1/3 in medical cost and 2/3 in productivity losses. (Corso *et al*., 2003)

2.2.1.4 Bacteria

Bacteria are single-cell organisms consisting of prokaryotic cells, which are the smallest and simplest structured cells (Maier *et al*., 2000). They could cause infections but in other areas of environmental microbiology they play a very important role as they are essential for many processes like nutrient cycling, waste disposal and plant growth. Properties and survival in different environment can vary substantially between different species. Generally the pathogenic bacteria are sensitive to disinfection and have higher infection dose than virus and protozoa (WHO, 2011).

Bacterial cells consist of a cell envelope and protoplasm containing a cell membrane, cell pool, ribosomes and a nucleoid. A protective cell wall or flagella for motility are also common attributes. Bacteria vary in size and shape. Common shapes are spheres or coccus, rods and helicals (spirals) but there are bacteria without well-defined shape as well, which are called to be pleomorphic, see Figure 2. Generally bacteria are larger than virus but smaller than protozoa. Typical size is 0.5-1 µm in diameter and a length of 1-2 µm (Maier *et al*., 2000). However, diameter could be as small as 0.3 µm and length could be as long as several 100 µm (Bitton, 1999).

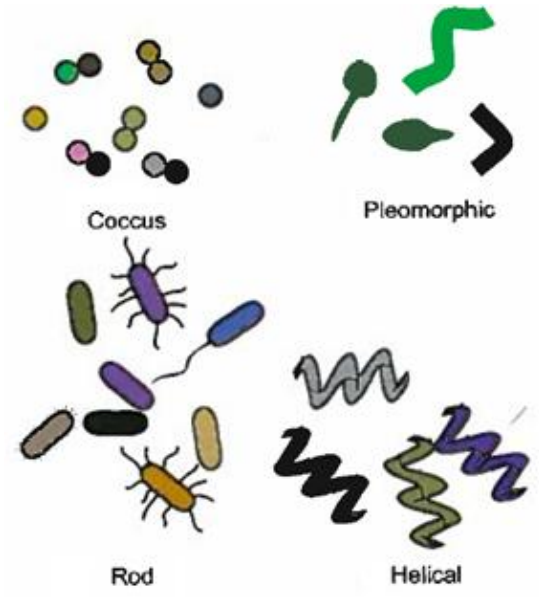

Figure 2 *Different shapes of bacteria (Maier et al., 2000). © Academic Press. Published with permission from Elsevier.*

Campylobacter spp. are curved spiral rods with a single unsheathed polar flagellum that occur in a variety of environments (WHO, 2011). In Sweden *Campylobacter* are the most commonly diagnosed waterborne pathogenic microorganisms (SMI, 2010a). It is mainly *Campylobacter jejuni* and *C. coli* that cause disease for humans. Approximately 7000 cases are reported annually in Swden, whereof 35 % are infected in Sweden. Probable reasons for the high disease number are that *Campylobacter* is excreted in large amounts with faeces, they are common in Swedish surface waters and the infection dose is relatively low. The bacteria exist both among humans and among different animal species and can be transferred between animals and humans. Food and water are important sources of campylobacter infections. One difficulty with tracing campylobacter infection from water is that there seem to be little relation between outbreaks with *Campylobacter* and presence of faecal indicator organisms in the water.

Shigella spp. are non-spore-forming, non-motile, rod-like bacteria (WHO, 2011). *Shigella* could cause outbreaks in Sweden, even though outbreaks are quite unusual. Approximately 400-600 cases of shigellosis are reported every year, whereof only 20 % are infected in Sweden (SMI, 2010). However, in other countries a number of large waterborne *Shigella* outbreaks have been reported (WHO, 2011). Infections are caused by four different species; *Shigella dysenteriae, S. boydii, S. flexneri* as well as *S. sonnei.*, which is the most common in Sweden (SMI, 2011b). The bacteria are most commonly transferred by food that has been irrigated with faecal contaminated water. It is also transferred by infected people prepare food for others or by direct contact as the infection dose is quite low.

Salmonella spp. are motile rod-shaped bacteria (WHO, 2011). There are two species, *Salmonella enterica* and *Salmonella bongori*, but earlier it was thought to be more than 2000 species. Infections are primarily spread by person-to-person contact, by consumption of contaminated water or food or by exposure to animals, depending on type of species. In Sweden *Salmonella* is primarily considered a food borne disease, even though food related native outbreaks are unusual too (SMI, 2011c).

Pathogenic *Escherichia coli* strains include several different classes, the most common being *Enterohaemorrhagic E. coli* (EHEC), *Enterotoxigenic E. coli* (ETEC), *Enteropathogenic E. coli* (EPEC), *Enteroinvasive E. coli* (EIEC). Waterborne transmission of pathogenic *E. coli* has been well documented for contaminated drinking-water as well as for recreational waters. Infection is associated with person-to-person transmission, contact with animals or consumption of contaminated water or food. (WHO, 2011) *EHEC* infections are a notification obligation disease with obligatory contact tracing in Sweden. *EHEC* is a toxin producing bacteria which is most commonly transferred by food but it could also transfer by water. It exists both among humans and animals and can be transferred between the two. In Sweden approximately 300 human cases of *EHEC* are reported every year of which half has been infected in Sweden. There are several different types which are pathogenic but the most common type during outbreaks has been EHEC O157. (SMI, 2012b)

2.2.1.5 Virus

Viruses are small obligate intracellular parasites which consist of either DNA or RNA surrounded by a shell of a protein called a capsid (Maier *et al*., 2000). They are technically not living organisms and require a host to grow and replicate. In general they are species specific and infect only one type of host; bacteria, plants or animals.

In general they can persist for long periods in water, they are less sensitive for disinfection than bacteria and they have a low infection dose. (WHO, 2011) They are also known to have high genetic variation and often evolve due to mutation (Maier *et al*., 2000).

Viruses also have varying sizes and structures. There are two main structures of the capsids; helical symmetry and icosahedrons (Maier *et al*., 2000). Icosahedrons are regular polyhedrons with 20 identical equilateral triangular faces, 30 edges and 12 vertices. The two main shapes can either be protected with an envelope or not and the icosahedrons can also have a tail. The different shapes can be seen in Figure 3. Generally, viruses are smaller than most other microorganism. Different species range in size from 18 nm up to several hundred nanometres.

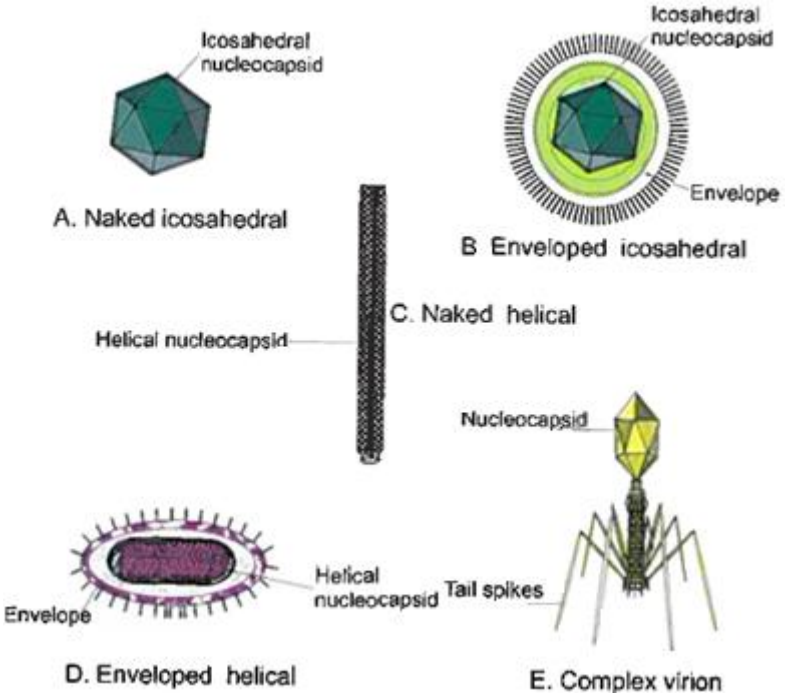

Figure 3 *Typical shapes of virus, with and without envelope ad tail (Maier et al, 2000). © Academic Press. Published with permission from Elsevier.*

Norovirus, or Norwalk virus as they also are called, are round-structured, single-stranded RNA viruses with a non-enveloped capsids (A, Figure 3) (WHO, 2011). They belong to the human calicivirus group and are the most commonly diagnosed virus species in connection to waterborne infections. *Norovirus* are very infectious and cause the winter vomiting disease. In 2010, 7500 cases were reported in Sweden, whereof 900 persons were infected in connection to four waterborne outbreaks (SMI, 2010b). The viruses exist in large amount in infected peoples faeces and could be transferred either by direct or indirect contact with infected persons, by drinking water or by contaminated food. *Norovirus* has a size of 20-35nm (Metcalf & Eddy, 2004).

Rotaviruses are wheel-shaped, segmented double-stranded RNA virus (WHO, 2011). They primarily infects children and are the most common reason for stomach disease for children aged 0.5-2 years but they can affect adults as well (SMI, 2011d). Rotaviruses are mainly transferred by person to person contact, but rotavirus has also been detected in sewage, rivers, lakes and treated drinking water (WHO, 2011). Even

though ingestion of drinking-water is not the most common transmission pathway for rotavirus, it is a public health concern if present in drinking-water as evidence suggests that rotaviruses are more resistant to disinfection than many other enteric viruses.

Enteroviruses are single-stranded RNA viruses. They are among the smallest known viruses. Enterovirus consists of approximately 70 virus types that infect humans, classified into the five groups; poliovirus, coxsackievirus A, coxsackievirus B, echovirus and enterovirus. Enteroviruses have been numerously detected in sewage, raw water sources, treated drinking-water supplies and foods. Main transmission pathways are person-to-person contact and inhalation of airborne viruses or respiratory droplets. Transmission from drinking-water could also be important as studies have shown that enteroviruses occur in considerable numbers in raw water sources and treated drinking-water supplies, but this has not yet been confirmed. (WHO, 2011)

Adeno- and **astroviruses** are two other virus species which typically are transmitted by the faecal-oral route that also have been detected in treated drinking-water and for which transmission by drinking-water seems likely but have not been confirmed (WHO, 2011). Though, the human adenoviruses are considered important for drinking water treatment purposes because they are exceptionally resistant to some water treatment processes, particularly to disinfection by ultraviolet (UV) light irradiation. The effectiveness of treatment processes for removal of human adenoviruses therefore needs validation and the preferred control measure is to prevent faecal contamination of source water.

2.2.1.6 Protozoa

Protozoa are single-celled motile eukaryotes which are more complex in structure than the prokaryotic cells (Maier *et al*., 2000). There is a huge variety of protozoa with different properties and they can exist in many types of environments. Some protozoa are parasitic. In general they are the group of pathogens that is least sensitive to inactivation by chemical disinfection, they can persist for long periods in water, and they have a low infection dose (WHO, 2011).

Protozoan cells are surrounded by a cytoplasmic membrane covered by a protective structure called pellucle (Maier *et al*., 2000). They can have many diverse forms but they typically have no cell walls. Protozoa range in size from 2 μm up to a few centimetres. Under adverse conditions protozoa form cysts or oocysts (Metcalf & Eddy, 2004).

Giardia lamblia, or *Giardia intestinalis* as they also are known as, exist in two different states in their life cycle, flagellate trophozoites and cysts (WHO, 2011). The cysts are sturdy and can survive for weeks or even months in natural waters. The trophozoites are bilaterally symmetrical and ellipsoidal in shape whereas the cysts are ovoid in shape, see Figure 4. It is the protozoon which is most commonly discovered in connection to outbreaks. Over 1500 cases are reported annually in Sweden (SMI, 2010c). Most infections are received abroad but there have been outbreaks within Sweden as mentioned before. *Giardia lamblia* exist both among humans and among different animal species. The protozoa are most commonly transferred by faecal contaminated water. It could also be transferred by food, usually if washed with contaminated water, or even sexually. It is the cysts which are infectious.

Giardia **Cryptosporidium**

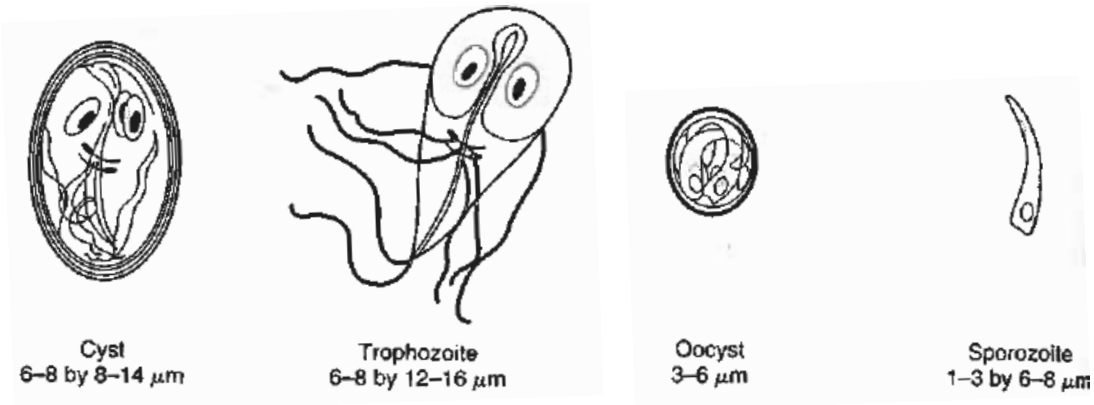

Figure 4 *To the left: Shape of Giardia lambia cyst and trophozite. To the right: Shape of Cryptosporidium parvum oocyst and sporozoite (Metcalf & Eddy, 2004). © McGraw-Hill Companies. Published with permission.*

Cryptosporidium spp. is the protozoa that have caused known waterborne disease outbreaks in Sweden (SMI, 2010d). There are a few different types of *Cryptosporidium*, of which *Cryptosporidium hominis* and *Cryptosporidium parvum* are the most common in connection to human outbreaks. *Cryptosporidium hominis* has only been found in humans whereas *Cryptosporidium parvum* is found in animals as well. Transmission pathways are through faecal contamination of water or food and through direct or indirect contact person-to-person. *Cryptosporidium parvum* exists in two different states in their life cycle, called sporozoilte and oocysts (Metcalf & Eddy, 2004). The oocysts are spherical and the sporozoiltes are crescent-shaped, see Figure 4. The oocysts are thick-walled and can survive for weeks or even months in fresh water (WHO, 2011).

Entamoeba histolytica exist either as replicative trophozoite or as cysts (WHO, 2011). It is the cysts, which are 10-20 µm in diameter, that are infectious. The main transmission pathways for entamoeba histolytica are person-to-person contact and contaminated food, although contaminated water is a significant mean of transmission as well and sexual transmission is possible*Entamoeba histolytica* infection is a notification obligation disease in Sweden with obligatory contact tracing and has been identified in connection to one waterborne outbreak in Sweden (SMI, 2010e).

Cyclospora cayetanensis is considered an emerging waterborne pathogen and transmission of *Cyclospora cayetanensis* by drinking water has been confirmed (WHO, 2011). The protozoa has thick-walled oocysts, about 8-10 µm in diameter, which are resistant to disinfection. Main transmission pathways are contaminated water and food.

2.2.1.7 Helminths

Helminths is a term used to describe parasitic worms. They are usually elliptical or egg shaped with widths between 20-50 µm and lengths between 45-70 µm. (Metcalf & Eddy, 2004) Since they are larger than the other pathogens they are easier to remove and therefore this group will not be further studied in this report.

2.2.2 Indicator organisms

Testing for presence of pathogens in water is relatively rare as analyses are often complex, time-consuming, costly and face problems with sensitivity of detection due to normally low concentrations (WHO, 2011). Instead faecal indicators organisms, usually bacteria, are normally analysed for surveillance of water quality and for verification and operational monitoring of treatment processes. Faecal indicator organisms are organisms which normally exist in the human intestines (Stenström, 1996) and therefore can be used to indicate faecal contamination of water. Faecal contamination of water in turn account for a greater risk of pathogenic microorganisms being present. An ideal indicator organism should fulfil a number of-criteria, see Table 3 (Maier *et al*., 2000).

Table 3 *Criteria which an ideal indicator organism should fulfil. Adopted from Maier et al. (2000).*

Criteria for ideal indicator organisms
They should be useful for all types of water
They should be present whenever the pathogen of interest is present
They should survive longer in the environment than the most persistent pathogen
They should not reproduce in natural waters
The analysis method should be relatively easy to perform
The density of the indicator organism should have some direct relationship to the degree of faecal pollution
They should be naturally present in faeces of warm-blooded animals including humans

In reality no indicator organisms fulfil all criteria (Maier *et al*., 2000). Therefore, testing for indicator organisms instead of pathogens is a somewhat uncertain method. Some pathogens are considerably more resistant than many indicator organisms so absence of indicators does not guarantee the absence of pathogens (WHO, 2011). Analyses of more than one indicator organism could increase the certainty since the more of the common indicator organisms that are present in a sample, the greater the risk that pathogens are present (Stenström, 1996).

Commonly used indicator bacteria are coliform bacteria, enterococci and clostridia. The coliform group has been used as faecal indicator organism for a long time. A customary parameter is total amount of coliforms, which includes all types of coliform bacteria, both faecal and environmental. However, not all coliforms have faecal origin and use of the parameter as indication of faecal contamination is therefore limited. *E. coli*, which belongs to the faecal coliform bacteria, is considered as the most suitable indicator of faecal contamination. It is commonly used in monitoring programmes for verification and surveillance of drinking-water systems. *E. coli* exist in faeces in large amounts and are highly specific of faecal pollution. The

disadvantage of *E. coli* is that they have less survival time than many pathogens and are less resistant to disinfection. (WHO, 2011) Coliform bacteria including *E. coli* are rod shaped in the size range of 0.5-2.0 µm (Levine *et al*., 2008).

Intestinal enterococci, which belong to the faecal streptococci, are more resistant to unfavourable conditions and disinfection than *E. coli* and tend to survive longer in aquatic environments (WHO, 2011). Also, most species do not multiply in the aquatic environment. Therefore, this group has become more commonly used as indicator organism for faecal pollution. However, they exist in human faeces in slightly less concentrations than *E. coli* and they could origin from other faecal sources than humans'. Enterococci are cocci-shaped and are in the size range of 0.5-1.0 µm (Levine *et al*., 2008).

The most important indicator organism in the clostridia group is the *Clostridium Perfringens* (Stenström, 1996). *Clostridium Perfringens* are exclusively of faecal origin, whereas other members of the clostridium group are not. They exist in small amount in human faeces but could also come from other sources. Closteridium produce spores, which are very resistant to disinfection and other unfavourable conditions and they have longer survival time in nature than other indicator organism as well as many pathogens. This makes them useful as indicator of old faecal contamination in raw water. They can also be used to assess the inactivation of protozoa and viruses in treatment processes. As the spores are very small, even smaller than protozoan cysts, *Clostridium Perfringens* could also be used as an indicator for filtration process verification. (WHO, 2011) They are rod-shaped and in the size range of 0.6-1.3×2.4-19.0 µm (Levine *et al*., 2008).

Besides the common indicator bacteria, coliphages are also commonly used as indicator organism. Coliphages is a virus that infects *E. coli* bacteria (Stenström, 1996). They are suitable as indicator for human viruses in treatment processes as they are similar in size.

2.2.3 Transport mechanisms

As soon as the pathogenic microorganisms enter a watercourse several environmental and biological factors will influence the dilution and the decay of these organisms. The change in concentration of the pathogenic microorganisms along a distance of a watercourse depend both on different transport mechanisms in the flow and different factors affecting the inactivation (Hartlid, 2009). Inactivation is when the pathogens die off or lose their ability to infect new hosts (Stenström 1996).

One important factor is the size properties of pathogenic microorganisms, which in aquatic environments influence the transport mechanisms in the way that most of the organisms have no other means of transport than by the water flow (Dechesne *et al*., 2006). This transport could be either freely by advection or attached to particles in the water.

The concentration downstream an emission point can be defined in a simplified way as a function of the dilution factor and the transport time (Sokolova *et al.*, 2012). The dilution factor can be calculated by dividing the transport mechanism into transport by lateral diffusion and transport by longitudinal dispersion (Hartlid, 2009). Lateral diffusion is caused by distribution and spreading by turbulence and molecular motions while longitudinal dispersion is caused by distribution and spreading due to the different water velocity through the cross section, see Figure 5.

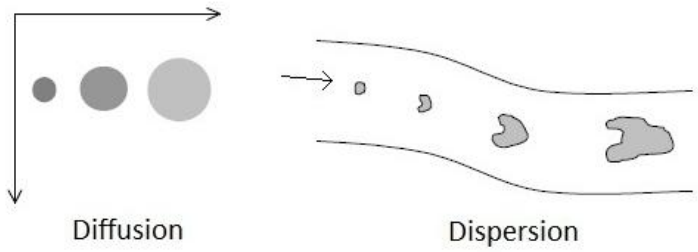

Figure 5 *Simplified sketch explaining the mechanisms of diffusion and dispersion with time.*

The inactivation of pathogens depends mainly on temperature, sunlight, pH and presence of predators (Stenström, 1996). According to Ferguson *et al.* (2003) temperature is seen as one of the most important factors that control the inactivation of pathogens and in general the die-off increases at higher temperatures. There are some variations between the species, however, the majority has a half-life of some days up to several months in colder water (Pond *et al.*, 2004).

2.3 Microbial removal in wastewater treatment

The removal of pathogens is particularly associated with removal of particles and suspended solids (Stenström, 1996) since the pathogens often are aggregated or adherent to suspended solids in the wastewater (WHO, 2008). An efficient treatment step for elimination of the suspended solids in the wastewater is therefore also likely to be efficient for microbial reduction.

Removal of suspended solids is to a great extent related to filtration and sedimentation. For microbial microorganisms, their small sizes influence the possibility of removal in these traditional wastewater treatment processes. Some larger protozoa and helminthes can be physically removed by sedimentation, but in most cases sedimentation is only significant when the pathogens are attached to particles large enough to settle (Dechesne *et al*., 2006). Removal of pathogens by filtration is also to a great extent connected with pathogens being attached to particles as filtration physically retains matter larger than the pore size of the filter media and the pores often are larger than the pathogens. However, some filter media, for example membrane filters, have pore sizes small enough to retain many pathogens. For filtration, properties like particle size distribution and concentration of suspended solids in the water play an important role together with the shape of the particles and the flocs in the wastewater influent. Therefore the following section describes the mechanisms that control the attachment of pathogenic cells to surfaces of particles and suspended solids.

Besides from sedimentation and filtration, considerable removal also occurs during aeration or by disinfection by e.g. chlorine, chlorine dioxide, ozone or UV radiation (Maier *et al*., 1999). However, disinfection mechanisms are not common processes for wastewater effluent in Sweden and North Europe and will not be discussed further.

2.3.1 Attachment to particles

The main mechanism that controls the attachment of pathogenic cells to surfaces of particles and suspended solids is adhesion. Adhesion is a physicochemical process

and the mechanisms behind the adhesion of microbial organisms are complex. When studying microbial adhesion, numerous interactions must be considered. Important factors are the properties of the microbial cell, the solid surface and the solution (Fletcher, 1996). The most important properties seem to be electrostatic interactions and hydrophobicity. Hydrophobic molecules are non-polar and thus water repellent which results in the molecules forming groups and cluster together in aquatic environment (Maier *et al*., 1999).

The theory of adhesion is called the Derjaguin-Landau-Verwey-Overbeek (DLVO) theory and it describes the interaction potential between charged surfaces interacting through a separating liquid medium (Hermansson, 1999). To enable adhesion, an initial interaction between the cell and the solid surface is required and this is possible when the cell is close enough to the surface (Maier *et al*., 1999). The cell can approach the solid surface in three ways; diffusion, active movement or convection.

Adhesion can be either reversible or irreversible. In the reversible state the cell is not in physical contact with the surface, see upper part of Figure 6, which means that it can easily be removed from the surface. In the irreversible state the cell is in actual contact with, or very close to, the particle surface. The initial reversible adhesion is controlled by electrostatic interactions together with van der Waals forces and hydrophobic interactions. Both hydrophobic interactions and van der Waals forces are attractive and initial adhesion is possible when they overcome the repulsive electrostatic forces. Figure 6 describes the interactions between electrostatic and Van der Waal's forces and show that when the cell surface is very close to the solid surface the attractive forces are very strong. At these short distances short-range forces like hydrogen bonding and ion pair formation are possible (Maier *et al*., 1999). If these forces can operate over time it enables interactions of cell surface structures or production of exopolymers which create an irreversible state between the cell and the solid surface. Differences in the ability of attachment to solids for various pathogens will affect the level of adhesion and consequently the degree of removal (Maier *et al*., 1999).

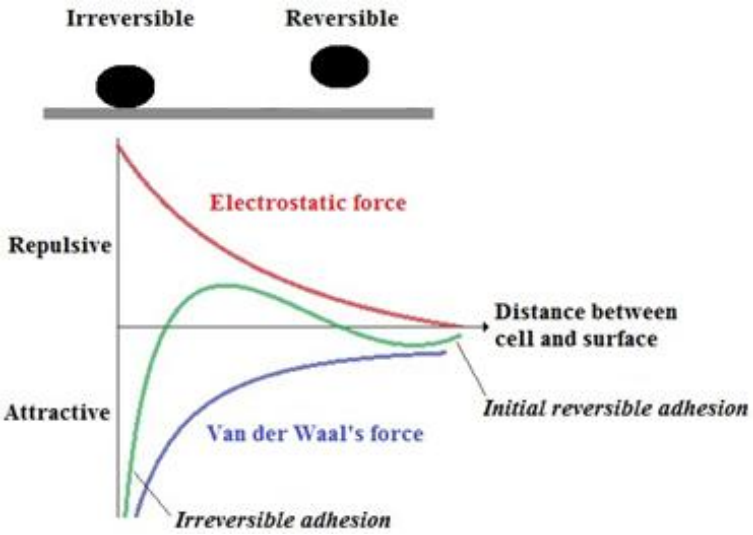

Figure 6 *Interaction between a cell surface and a solid surface depending upon electrostatic forces and Van der Waal's forces.*

According to Maier *et al*., (1999) two trends that have an impact on the microbial cell adhesion can be distinguished. First, adhesion increases with increasing

hydrophobicity of either the cell or solid surface. Second, adhesion generally increases with decreasing cell surface charge. Moreover, a reduction of the cell radius will in general reduce the total adhesion interaction (Hermansson, 1999).

2.3.2 Coagulation/flocculation

The naturally occurring adhesion in wastewater generally does not affect the attachment of pathogenic microbial content to suspended solids enough to get sufficient removal efficiency. One way to accelerate and increase the adhesion process is to use a chemical coagulant. Chemical coagulation is a destabilization process where the forces that keeps particles apart is neutralized and as a result lets the particles collide to form larger particles through flocculation (Metcalf & Eddy, 2004). A flocculant can also be used to improve the flocculation process.

As can be seen in Figure 6 the repulsive electrostatic force between particles must be reduced, neutralized or inverted to enable pathogenic microorganisms to attach to each other or to suspended solids in the water. Through coagulation this is achieved by adding a chemical substance, which neutralize the negatively charged particles so that the distance between the particles can be decreased and the Van der Waal's forces get enabled. The coagulants can be divided into two main categories; metal ions and polyelectrolytes (polymers). (Metcalf & Eddy, 2004) The most frequently used coagulants in Sweden are different aluminium or iron based mineral salts (Hansen, 1997). Lime stone addition has also proved to result in significant reduction of pathogens (Maier *et al*., 1999).

The mechanisms behind coagulation and flocculation are complex, depending on many properties and will not be further discussed here. It seems though to be an important step in treatment processes to reach sufficient removal efficiency of pathogenic microorganisms in combination with disc filters

2.4 Conventional wastewater treatment

Conventional wastewater treatment is a combination of mechanical, chemical and biological treatment designed to remove particles, biological degradable material and nutrients, mainly phosphorous (Berg, 2012). The last 20 years it has become more and more common to also have some kind of nitrogen removal as nitrogen is an important nutrient as well.

Figure 7 shows an example of a typical modern wastewater treatment process. The mechanical treatment step is considered primary treatment and involves screens and grit chambers for removal of coarse materials and sand as well as preliminary sedimentation where larger particles settle. The biological and chemical treatment is called secondary treatment. In the biological treatment bacteria are used for biological degradation, often in an activated sludge process. In the chemical treatment flocs are created from smaller particles using a chemical coagulant which usually are allowed to settle in a sedimentation basin. In excess of this, different tertiary treatment processes could also be used to improve the treatment, for example different types of filtration systems, including disc filters, are sometimes used.

Chemical and biological treatment with or without nitrogen removal is the most common treatment process in Sweden. More than a third (36 %) of the households in

Sweden connected to sewage treatment plants are connected to plants with treatment with nitrogen removal and 58 % without nitrogen removal (Svenskt Vatten, 2000). The remaining households only have chemical or biological treatment. Stricter effluent quality limits of nitrogen during recent years have forced many treatment plants to improve their treatment or plan for that in the near future.

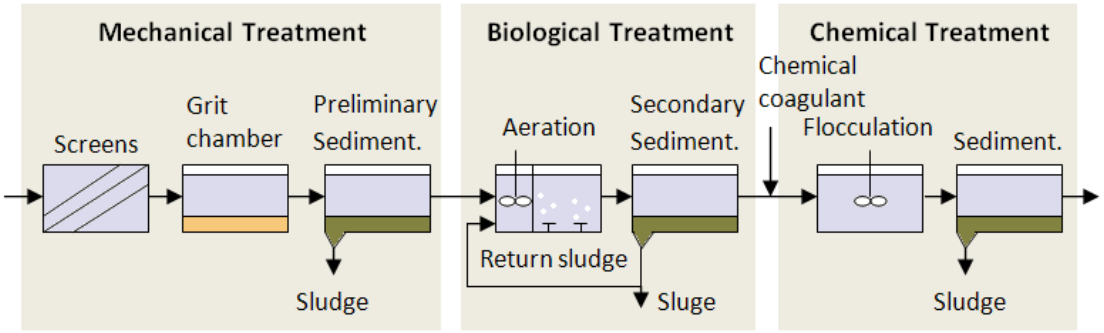

Figure 7 *A typical modern wastewater treatment process including mechanical treatment, biological treatment and chemical treatment.*

2.4.1 Removal efficiency of pathogens

In conventional wastewater treatment systems the removal efficiency of microbial content varies depending on the type of treatment processes. The differences in removal efficiencies are large and depend on several characteristics and properties of both the WWTP and the incoming wastewater. Factors such as process type, retention time, biological flora present in activated sludge, oxygen concentration, pH, temperature and the efficiency in removing suspended solids (Koivunen *et al*., 2003) are some of all the factors of importance. As pathogen removal depends on many variables and as there is a large variety of different treatment processes, it is difficult to specify the removal efficiency.

Though, many processes have been showed to significantly remove pathogens. Removal between 80-99.9 % is common and could be achieved for example by the biological activated sludge process (Bitton, 2000).

2.5 Disc filters

Disc filtration has during recent years become a more and more common technique to use as a final polishing tertiary treatment step at WWTPs. The low cost, easy adaptation to changing needs and the small space requirements makes disc filters a preferred choice of tertiary treatment compared to more traditional solutions for many WWTPs (Persson *et al*., 2006), like sand filters. Other possible use of disc filters are filtration of raw water and for water recirculation processes. The knowledge about the removal efficiency of pathogens in wastewater is more limited. Only some minor test campaigns have been carried out (Gómez *et al*., 2006; Åström & Pettersson, 2007a; Wilén *et al*., 2012). A short description of disc filters and what is known about their removal efficiency for pathogens is presented below.

2.5.1 Function

There is a wide range of available disc filter manufacturers on the market. The technology is overall similar, however with some variations. The general function of a disc filter is a micro screen filtration process where particles in the water which are larger than the filter pore size are physically retained. The differences between the different manufacturers primarily concern the technical design, the operation of backwashing, the pore size and the working environment (Persson *et al*., 2006).

A disc filter consists of a rotating drum with 1-20 filter panels, each of them often divided into six segments. Each segment is covered by a stretched filter media (Persson *et al*., 2006). The material used as filter media is typically either polyester or stainless steel (Type 316) and the pore size is normally 10-30 µm or larger (Metcalf & Eddy, 2004).

The secondary treated influent water enters through a feed tube in the centre of the drum into the filter panels, see Figure 8. Since the water level inside the filter panels is higher than in the channel outside the filter, a pressure difference is created which will press the water through the filter media. Each filter panel have a stretched filter media on both sides and the water, entering in the middle of the panel, is consequently filtered from the inside and out, see the right part of Figure 8.

A thin sludge film will build up inside the filter panels, which will further raise the pressure difference and consequently raise the water level inside the panels (Metcalf & Eddy, 2004). When the sludge film reaches a certain thickness, the rotation and the backwashing of the filter starts. Filtered effluent water is then sprayed from the outside on both sides to flush away the sludge film. The sludge water is then collected and transported away from the filter through a gutter. For most of the disc filters the filtration can be either constant with continuous backwashing or it can be intermittent.

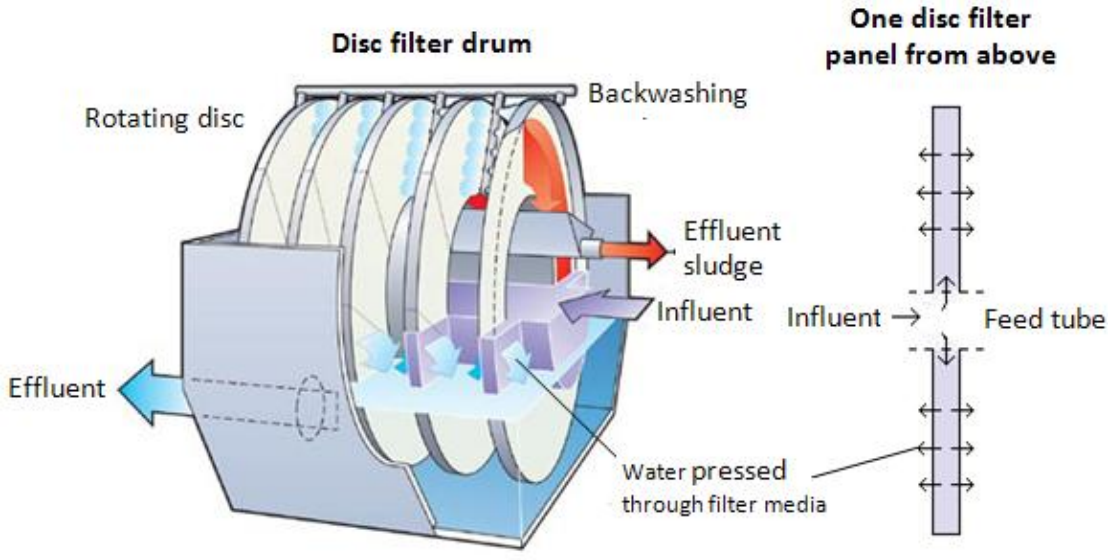

Figure 8 *Schematic drawing over a disc filter. Modified picture (Gryaab, 2011). Published with permission from Hydrotech.*

When disc filters are used as a tertiary treatment step, larger particles have to a large extent already been removed and the influent therefore contains mostly smaller particles. To remove these particles in a disc filter, a very fine pore size is required

which will result in low hydraulic capacity (Mattsson, 2005). For disc filters with coarser pore sizes, the removal efficiency could be improved by the use of coagulation/flocculation prior to the filters in order to create larger and more stable particles, see Figure 9.

Coagulation/flocculation prior to disc filtration is a quite new technique which has not yet been used for tertiary disc filters in Sweden. However, Trollhättan Energi, who is responsible for the WWTP in Trollhättan municipality, will install disc filters with coagulation/flocculation prior to the filters at Arvidstorp WWTP during 2013.

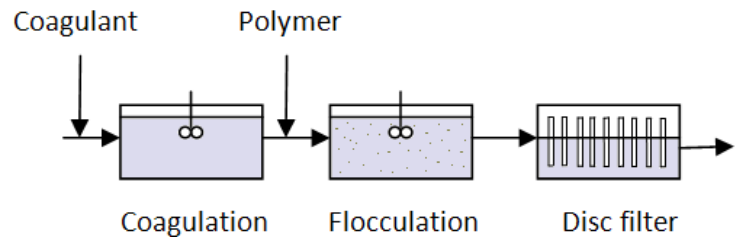

Figure 9 *Disc filter with coagulation and flocculation prior to the filters.*

2.5.2 Removal efficiency of pathogens

The general function of filtration with disc filters is that all particles bigger than the pore size would be retained, so the most important separation mechanism is physical blocking. As the pore size normally is considerably larger than the approximate size of the different microorganism groups, see Table 4, the removal will depend on the ability of the microorganisms to attach to larger particles in the wastewater. Results from previous investigations have shown good removal efficiency for particles (Persson *et al*., 2006).

Table 4 *Typical size ranges for microbial pathogens are typicaly smaller than disc filter pore sizes. D=diameter, L=length*

Pathogen group	Size
Bacteria	D 0.5-1 µm, L 1-2 µm
Protozoa	>2 µm
Viruses	0.018-0.5 µm

<

Disc filter pore size
10-30 µm

Previous investigations of removal efficiency of disc filers have showed some but limited removal of pathogens. The studies have been very limited and all of them conclude that more research is needed to verify the results. Studies on pathogen removal efficiency for disc filters where coagulation/flocculation is used prior to the filters have been found. When the planned disc filters facility in Arvidstorp WWTP, in Trollhättan, is up and running, Trollhättan Energi will perform measurements on the pathogen removal efficiency with coagulation/flocculation.

Gómez *et al*. (2006) studied the removal efficiency for microbial contamination by filtration technologies, including disc filter, with the aim to evaluate if filtration could be used as an alternative to traditionally wastewater disinfection. The analyses indicated that the disc filter had a low removal capacity for both faecal coliforms and *E. coli*. The removal for faecal coliforms was 31 ± 21 % and for *E. coli* 33 ± 32 %. A high correlation could be seen for the effluent concentration as a function of the influent concentration for both indicator organisms.

A pilot study of disc filters at Rya WWTP, (Åström & Pettersson, 2007a) assessed the removal efficiency for microbial organisms by performing garb sampling in a disc filter with a pore size of 10 µm. The results showed that the disc filter reduced bacteria by 0.5 to 1 log units or 50-90 % whilst the separation of virus was almost negligible. It was concluded that the viruses probably passed the filter while the bacteria to some extent were retained either physical or by electrostatic binding. Åström & Pettersson (2007a) also underlined the fact that there was unusually high amounts of suspended solids at the point of testing, which could imply that higher amounts of viruses and bacteria than usual were removed.

In addition, as a part of a study of sludge particle removal in wastewater by disc filtration, Wilén *et al*. (2012) performed a lab-scaled assessment of the removal efficiency of indicator organisms by filtration through cloths with pore size 10-40 µm. The results showed poor reduction of indicator organisms.

2.6 Sand filters

Sand filtration is a method which is commonly used for particle and pathogen removal in drinking water treatment. Another, less common, use of sand filters is for wastewater treatment where they usually are used as a polishing step at the end of the treatment process, mainly to further reduce the nutrient and particle concentrations. The use of sand filters as a pathogen barrier in drinking water makes it interesting for pathogen removal in wastewater treatment plants as well. Some studies have previously been done within this area. To allow comparison of disc filters with another option for tertiary treatment, a short description of sand filters and what is known about their efficiency for pathogen removal is presented below.

2.6.1 Function

Sand filtration is a process where suspended solids are removed from a liquid as it passes through a bed of sand (Metcalf & Eddy, 2004). Different types of sand filters are well described in literature but the literature specify slightly different data. There are two main types of sand filters which differ from each other in several ways; rapid sand filters and slow sand filters.

Rapid sand filters consist of graded beds with coarse sand grains. In the filtering process, the water flows at high velocity. The water is directed through a bed of sand where particles are retained between or attach to the filter grains throughout the depth of the bed. To keep good removal efficiency it is important to operate the filters under the correct circumstances. The removal efficiency depends on several factors. One important factor is that the filters require regular backwash every few days since pressure drop increases as particles build up. After backwashing, the removal efficiency is lowered initially. (Dufour *et al*., 2003) The exception is continuous sand

filters where dirty sand continuously is removed, cleaned and returned to the sand bed. This method has the advantage of a non-interrupted filtering process (Sjöberg, 2005).

Slow sand filters consist of a bed of fine sand and operate at a lower flow velocity (Dufour *et al*, 2003). The main treatment is in the top 20 mm where a biologically active layer is formed, the Schmutzdecke. The Schmutsdecke provides efficient removal and biological degradation of very small particles. Slow sand filters do not use backwashing. Instead they are cleaned by scraping the Schmutsdecke off every few weeks or months when particles have built up and flow rate has declined. This takes the entire filter out of service and it takes a while before the filter can operate at normal conditions again.

According to Dufour *et al*. (2003), rapid sand beds are approximately 0.6-1.0 m deep and the sand grains are around 1 mm in diameter whereas slow sand filters are approximately 0.7 meters deep and sand grain are 0.15-0.35 mm. The flow velocity in rapid filters is often between 5-15 m/h and slow filters operate at a flow velocity of approximately 0.1-0.3 m/h.

Advantages with slow sand filters are their effectiveness for pathogen and particle removal through degradation and the low need for operation and maintenance (WHO, 2012a). Disadvantages are their vulnerability for clogging at high turbidity, the amount of space needed and that they have to be taken out of service to be cleaned. An advantage with rapid sand filters is that they are more space efficient (WHO, 2012b). Disadvantages are that filtration without coagulant will not give adequate water quality and that they require trained staff and frequent checking for optimal operation.

2.6.2 Removal efficiency of pathogens

Rapid sand filtration is essentially a physical filtration process whereas slow sand filtration is a biological process (Dufour *et al.*, 2003). That means that the pathogen/particle attachment/pore size relationship is more important for rapid sand filtration.

Rapid sand filtration in combination with coagulants may remove 2-3 log units (99-99.9 %) of bacteria (Dufour *et al*, 2003). For viruses reported removal efficiency is 1-3 log units (90-99.9 %) and for parasites the removal is 2-3 log units (99-99.9 %).

A study by Koivunen *et al*. (2002) showed that tertiary rapid sand filtration in combination with a coagulant was an efficient step for removal of microorganisms as well as suspended solids and nutrients from secondary treated wastewater. The tertiary filtration resulted in an additional pathogen removal of 2 log units (99 %) compared to treatment without tertiary treatment. For filtration without coagulants the removal efficiency dropped to 25 %. The much less effective microbial reduction could be explained by the remaining particles being small and therefore will go through the filter pores (Koivunen *et al*., 2002). However, coagulants are usually used in combination with rapid filtration.

Slow sand filters have higher efficiency in removing bacteria and parasites and does not need coagulants as a pre-step (Dufour *et al*., 2003). If well maintained they could have similar efficiency as rapid filters in combination with coagulants.

In a study performed by Langenbach *et al*. (2009) on slow sand filters as tertiary treatment for pathogen showed that slow sand filters reduced faecal indicators by 1.9-3.0 log units or 98.9-99.9 %. Use of finer and more homogeneous sand or larger surface resulted in better removal efficiency. This is consistent with what other studies in the literature say about factors that affect the overall removal efficiency of slow sand filters.

3 Method

In this chapter the approach to investigate the removal efficiency as well as the risk assessment method are described. For the investigation of the risk reduction potential for raw waters by installation of disc filters, data on removal efficiency of pathogens by disc filters was required. To determine the removal efficiency, a measurement campaign was performed on the disc filter treatment step at Rya WWTP in Göteborg. Concentrations of microorganisms were measured in the influent and in the effluent. This was carried out over individual disc filters units and over the whole disc filter facility, i.e. over all filter lines. The results from the measurements were then used to calculate the removal efficiency of the disc filter step for some microbial indicator organisms and pathogens.

A risk assessment was performed on the surface raw water source River Göta älv. This included an inventory of the WWTPs along Göta älv, the current microbial risk picture from the WWTPs and what the reduced risk would be if disc filters were installed at all WWTPs along the river. The risk reduction potential was calculated for Göteborg's raw water intake Lärjeholm as well as for the drinking water consumers in Göteborg municipality. An inventory of the treatment process in the drinking water plant Alelyckan was therefore also necessary. The result from the risk assessment was then used for drawing conclusions of the risk reduction potential by installing disc filters in WWTP in general.

The measurement campaign including the removal efficiency calculation and the risk assessment are further described below.

3.1 Measurement campaign

The disc filter facility at Rya wastewater treatment plant in Göteborg was chosen as study object since the convenient location and the up- and running disc filters made it appropriate for measurements. Disc filtration with coagulation/flocculation prior to the filters was not studied since this setup was not available at the plant.

3.1.1 Rya WWTP disc filter facility

Rya WWTP initiated the installation of the disc filter facility, which is located as a last treatment step, during 2006 and it was finished for operation in 2010 (Gryaab, 2011). The main purpose for the disc filter installation was to meet the stricter phosphorus limit of 0.3 mg/l for the effluent water by reducing the particle bound phosphorous.

The disc filter facility consists of a large building divided into two large halls with a total of 32 disc filters connected in parallel (Gryaab, 2011). The future capacity however is 40 disc filters. One of the disc filter halls can be seen in Figure 10. Each filter has 20 rotating discs with a combined filter area of 112 m^2. This gives a total filter area of 3584 m^2. The type of disc filter used at the plant is Hydrotech HSF2220-2FN. The disc filters have a pore size of 15 µm and a capacity of 900 m^3 per hour and filter. The filter media is a twill weave monofilament polyester filter cloth (Persson *et al*., 2006).

The backwashing cycle is 10 s, which gives a total demand for water of around 30 m^3/h and filter (Gryaab, 2011). The filtration is a continuous process even though the backwashing is in progress. There are also two additional systems for cleaning of the filter media to deal with the problem of precipitation that clogs the filter media over time. Cleaning with diluted hydrochloric acid takes place approximately every third week and cleaning with sodium hypochlorite takes place two times a year.

There are two separate inflows to the disc filter facility. One part of the water comes from the post denitrification (PD) and the other part comes from the secondary settling (SS). The PD consists of moving bed biofilm reactors (MBBR). The SS consists of sedimentation basins for the sludge particles from the previous activated sludge process.

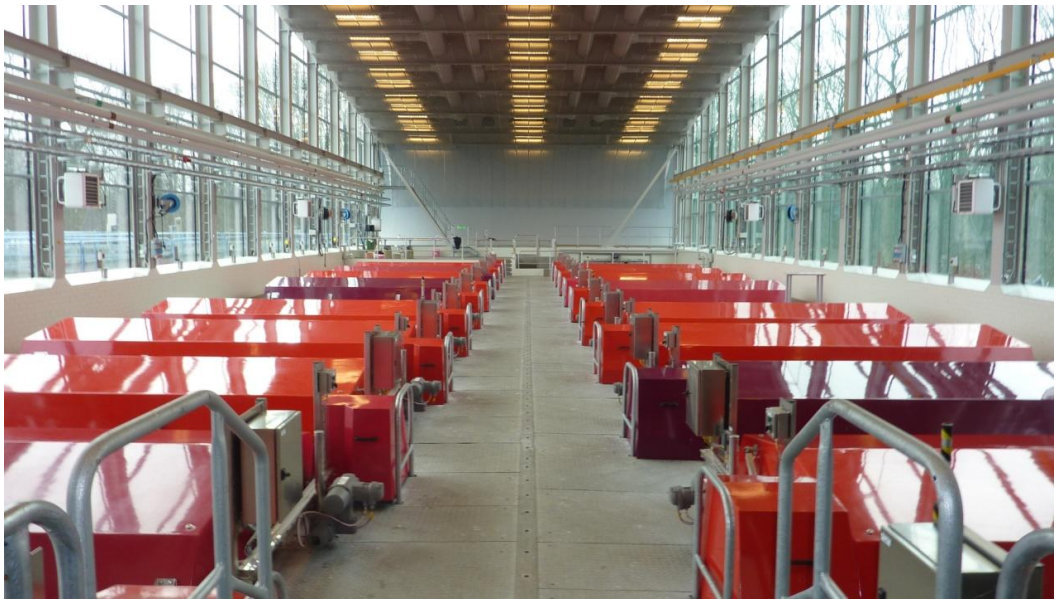

Figure 10 *One of the disc filter halls in the disc filter facility at Rya WWTP. Photo: Emma Stenmark*

3.1.2 Water quality parameters

Different types of microorganisms have different characteristics, e.g. size, shape and attachment properties, which will affect their ability to attach to particles and get retained in the filter. This makes it reasonable to assume that the removal efficiency differ between microorganisms.

However, testing for the presence of all pathogen types specifically would not only be complicated, take lots of time and be expensive, but would not guarantee useful results as the presence of a specific specie is not granted at all times. To get higher probability of useful results, some faecal indicator bacteria were analysed. The common faecal indicator bacteria *E. coli*, enterococci and total coliforms were chosen to facilitate comparison with other studies. Coliphages and *Clostridium Perfringens* were analysed since they are good indicator organisms for both virus and protozoa.

Preferably, a few specific pathogens from both the virus and protozoa group should also have been chosen. *Norovirus* and *Giardia* are interesting as they are the most commonly detected pathogen in Sweden (SMI, 2011). *Cryptosporidium* is also of interest since it is the pathogen which has caused the largest known waterborne disease outbreak in Sweden. However, as analysis of the two later were not available, *Norovirus* was the only specific pathogen analysed.

Since the separation of pathogens is related to the general separation of particles, an investigation of the content of suspended solids as well as a particle size distribution analysis was also performed. Removal of small particles could also act as an indicator of the removal of protozoa. Also, total phosphorous (P_{tot}) and total nitrogen (N_{tot}) content was analysed. This will set the sampling conditions in context to annually variations of content and removal efficiency.

3.1.3 Sampling locations

The water samples were collected at seven locations within the disc filter facility, see Figure 11. The sample locations A and B are located at the influent from the post denitrification and secondary sedimentation and location C at the combined outlet. These locations were chosen to give an indication of the removal efficiency for the entire disc filter facility including all filter lines.

Sample locations $D_{1, 2}$ and $E_{1, 2}$ are located at the inlet and at the outlet at two different disc filters. These locations were chosen to provide the removal efficiency for one single disc filter. Two different filters were studied as the influent to the facility originates from the two different treatment processes. In a previous study of disc filters at Rya WWTP (Yimamu, 2012) it was showed that the particle composition diverges between the influent from the PD and from the SS. The study indicated a higher content of small particles in the effluent from the secondary sedimentation whilst the effluent from the post denitrification contains a higher content of larger particles. As the removal of pathogens is expected to be connected to the removal of the particles, this makes it reasonable to assume that there will be some difference in removal efficiency for the different influents.

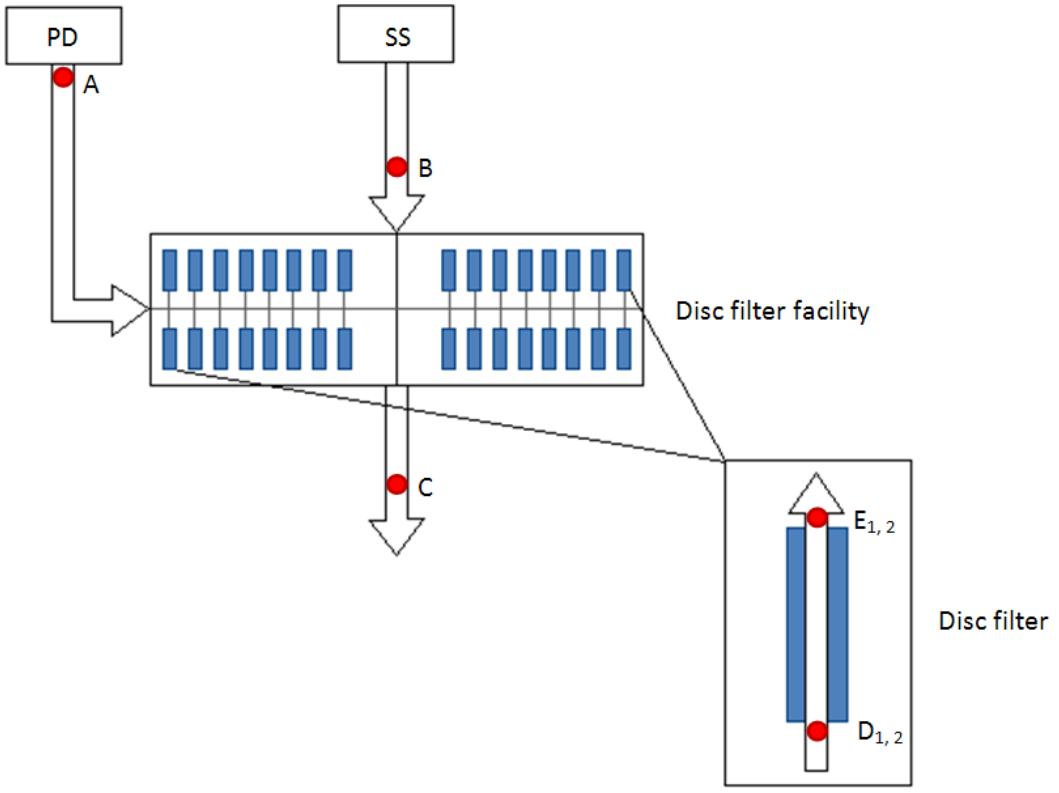

Figure 11 *Schematic drawing of the disc filter facility with sampling locations A-E marked by red dots.*

The water from the two inflows A and B will mix somewhere in the disc filter building depending on the current capacity of the two treatment processes. This means that some filters receive mixed water from both PD and SS and others receive water mainly from one or the other. To allow comparison between two different influent water qualities one filter mainly feed from the PD and one filter mainly feed from the SS was chosen.

3.1.4 Sampling procedure

The measurement campaign consisted of two sampling rounds. The first part of the measurement campaign was more extensive and was performed during the period 6-8 March, 2012. This period was chosen as many waterborne outbreaks occur during the winter months, which should increase the chance of detecting pathogens during this period. *E. coli*, total coliforms, enterococci and *Norovirus* as well general water parameters were analyzed this time. The second smaller sampling round was performed during the period 28-30 May, 2012. In the second round the only parameters analysed were microorganisms as these were the most uncertain parameters. This time coliphages and *Clostridium Perfringens* were analysed instead of total coliforms and enterococci since these are better indicators for *Norovirus* and *Cryptosporidium* respectively.

The plant was planned to run under normal conditions during both periods. Would anything yet be abnormal, this should be detected by Gryaabs continuous measurements of several water parameters. Each filters where cleaned with acid the day before the first sampling round. This means that bio film build-up was very limited during this sampling and that conditions in both filters were equal. The second sampling round was performed two weeks after the last acid cleaning to investigate if this would result in higher removal efficiency due to build up. The weather conditions during sampling should not have a major significance as simulations made by Åström & Pettersson (2009) shows that there is little difference in pathogen concentrations in effluent between dry and wet weather periods.

The sampling scheme for the first sampling period can be seen in Table 5. A total of 37 samples were collected, 25 for indicator analysis and 12 for *Norovirus* analysis. All samples were collected into plastic bottles and were kept in refrigerator and/or cool bag until analysis.

Composite sampling during one hour over the entire disc filter facility was performed on the 8th of March. Four subsamples of ~500 ml were collected every fifteen minutes between approximately 9.50 to 10.50 at the influent from the PD, the influent from the SS and in the total effluent from the disc filter facility. The four subsamples at each location were then mixed thoroughly providing composite three samples.

The sampling over the two individual disc filter units was performed in two rounds, each 24 hours. The disc filters were operated continuously during the 24 hours period the sampling was carried out. Sampling over a disc filter receiving water from the PD was performed 6-7 March with start 9.10. When the automatic water sampler had been running for 24 hours the equipment were carefully cleaned and moved over to a disc filter receiving water from the SS, where sampling was performed 7-8 March with start 10.20. Samples for particle analysis were also taken over the two individual disc filter units with momentary grab performed on 8 March.

Table 5 *Samples collected at each sample location and method used for sampling for the first sampling period 6-8 March, 2012.*

Sample location	Microorganisms analysed	Sampling method	Number of subsamples	Subsample volume (ml)	Number of samples
A	Indicator organisms	Composite 1h	4	500	Triplicate
B	Indicator organisms	Composite 1h	4	500	Triplicate
C	Indicator organisms	Composite 1h	4	500	Triplicate
D_1 Inlet PD	Indicator organisms	Composite 24h + Momentary	24	500	Triplicate + Single
	Norovirus	Composite 24h	24	400	Triplicate
E_1 Outlet PD	Indicator organisms	Composite 24h + Momentary	24	400	Triplicate + Single
	Norovirus	Composite 24h	24	400	Triplicate
D_2 Inlet SS	Indicator organisms	Composite 24h + Momentary	24	400	Triplicate + Single
	Norovirus	Composite 24h	24	400	Triplicate
E_2 Outlet SS	Indicator organisms	Composite 24h + Momentary	24	400	Triplicate + Single
	Norovirus	Composite 24h	24	400	Triplicate

Portable composite samplers ISCO 6700 and ISCO 3700 from Teledyne ISCO were used for the sampling. They were installed in slots to the inflow and outflow channels located directly before and after the disc filters, see Figure 12. The samplers had 24 plastic bottles each, into which subsamples of ~400 ml was collected every hour. After the 24 hours, for both samplers individually, all 24 subsamples were mixed thoroughly to a composite sample. The composite samples were then analysed in triplicate to increase the certainty of the results.

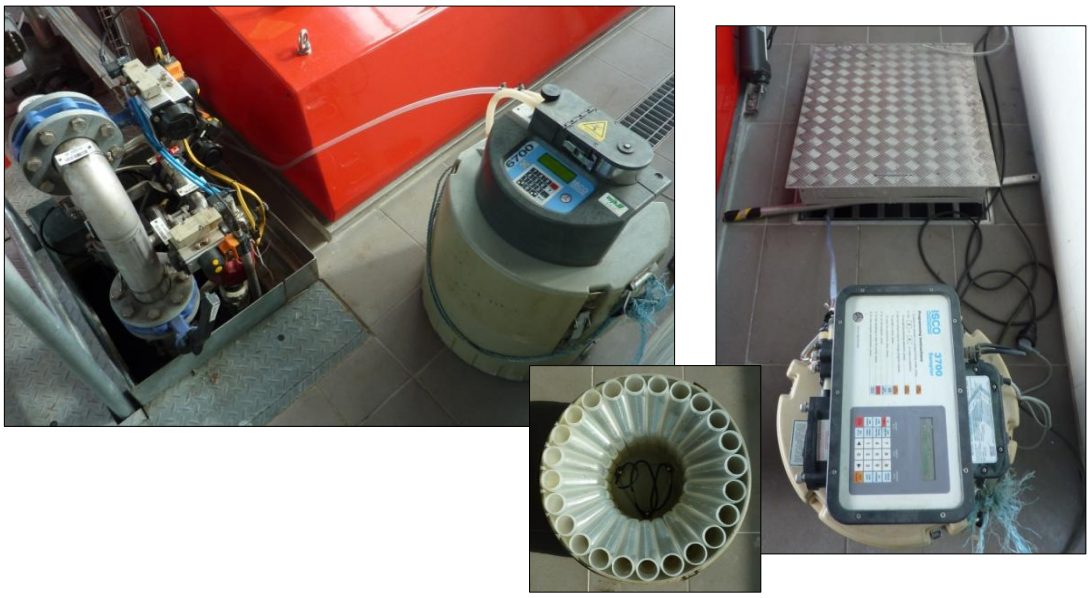

Figure 12 *To the left the ISCO6700 sampler installed in a slot at the inlet to a disc filter. To the right the ISCO3700 sampler installed in a slot at the outlet from a disc filter. The samplers had 24 plastic bottles each, into which samples were collected every hour. Photo: Emma Stenmark*

In case any problems would arise with the samplers, momentary grab samples were also taken in parallel with the composite samplers. These were taken in the filters just before and after the discs, see Figure 13, and were only analysed as single samples.

Figure 13 *An open disc filter, in which the momentary grab samples over the filter were taken. Photo: Emma Stenmark*

The second sampling was conducted in a similar way as the first was but in a smaller scale. Again subsamples were collected using composite samplers for 24 h over two individual disc filter units, fed from PD and SS respectively. Total 8 composite samples were collected, whereof 4 for indicator analysis and 4 for *Norovirus* analysis. The sampling scheme for the second sampling period can be seen in Table 6.

Table 6 *Samples collected at each sample location and method used for sampling for the second sampling period 28-30 May, 2012.*

Sample location	Microorganisms analysed	Sampling method	Number of subsamples	Subsample volume (ml)	Number of samples
D_1 Inlet PD	Indicator organisms	Composite 24h	24	400	Single
	Norovirus	Composite 24h	24	400	Single
E_1 Outlet PD	Indicator organisms	Composite 24h	24	400	Single
	Norovirus	Composite 24h	24	400	Single
D_2 Inlet SS	Indicator organisms	Composite 24h	24	400	Single
	Norovirus	Composite 24h	24	400	Single
E_2 Outlet SS	Indicator organisms	Composite 24h	24	400	Single
	Norovirus	Composite 24h	24	400	Single

3.1.5 Analysis methods

The analyses of indicator organisms were carried out at the laboratory at Lackarebäck WTP in Göteborg and the *Norovirus* analyses were carried out at the laboratory at Länsjukhuset Ryhov in Jönköping.

E. coli and total coliforms were analysed with the *Colilert-18 Quanti-Tray/2000 (IDEXX)* method and intestinal enterococci were analysed with the *Method by Membrane filtration (ISO 7899-2:2000)* method. For both methods the maximum concentration of microorganisms in the water that can be analysed is limited. To get analysable concentrations, the samples were diluted in different proportions in peptone water before the analyses (1 ml and 0.01 ml sample/100 ml peptone water for Colilert-18, 1 ml, 0.1 ml, 0.01 ml and 0.001 ml for enterococci) and well shaken. Coliphages were analysed with the *Enumeration of somatic coliphages (ISO 10705-2)* method and *Clostridium Perfringens* were analysed with the *Method by membrane filtration (ISO/CD 6461-2)* method, which account for presumptive *Clostridium Perfringens*.

Norovirus was analysed using the method *Real-time Polymerase Chain Reaction (PCR)*. In the PCR method the sampled water is first centrifuged in low speed were a

pellet of particles is created and thrown away (Nordgren e*t al*, 2009). The remaining supernatants are saved and ultra-centrifuged to a pellet to concentrate the virus. From the pellet RNA is extracted and through reverse transcription complementary DNA (cDNA) is produced. The *Norovirus* concentration is then calculated from the cDNA by use of a real-time PCR assay. This is achieved by the number of viral genomes from the PCR reaction which enables an estimation of the number of *Norovirus* particles per litre, for each genogroup.

The analysis of suspended solids, P_{tot} and N_{tot} was performed in connection with the sampling and was performed at laboratory at Rya WWTP by Gryaab. The particle distribution analysis was also carried out at Rya WWTP using water particle counter *WPC 1000, ARTI, Art Instrument, Inc*.

3.1.6 Removal efficiency calculations

The average removal efficiency of each microorganism for the disc filter unit feed from PD, the disc filter unit feed from SS and for the entire disc filter facility were calculated from the average concentration of the triplicate samples. The standard deviation of the samples was also considered. The removal efficiency (R) was calculated as the concentration of microorganisms before disc filters/disc filter facility (C_{inlet}) minus the concentration after disc filters/disc filter facility (C_{outlet}) divided by the concentration before, see Equation 1. For the samples over the entire disc filter facility, an average inflow concentration of indicator organisms first had to be calculated based on the concentration in each inflow and the corresponding flows.

$$R = \frac{C_{inlet} - C_{outlet}}{C_{inlet}} \times 100\% \qquad [1]$$

The removal efficiencies were evaluated in order to assess the influence of the incoming water quality as well as possible differences between removal efficiency of one filter unit and the entire facility. From the different sampling locations an average removal efficiency of each microorganism was assessed and used as input for the risk assessment.

Besides the removal efficiencies of the different microorganisms, the removal of particles, suspended solids, P_{tot} and N_{tot} at the time of the measurements were also calculated. The function of the disc filter facility at the time of the measurements was then compared to the rest of the year using results from previous measurements of P_{tot}, N_{tot} and suspended solids over the year, in order draw conclusions of how the pathogen removal changes over a year.

Removal of suspended solids, P_{tot} and N_{tot} were calculated from inlet and outlet concentrations in similar way as for microorganisms. Particle removal efficiency was calculated using data from the particle distribution analysis. If spherical particles were assumed, average particle diameter and number of particles could be used to calculate particle volumes in influent and effluent. From this, separated particle volume and removal efficiency of particles were calculated. Suspended solids removal was calculated using continuous measurements of suspended solids at the inflow and outflow to the disc filter facility as well as analysis of the momentary samples.

3.2 Risk assessment

Göteborg's raw water intake at Lärjeholm was chosen for the risk assessment to investigate the risk reduction potential of installing disc filters because it is located closest to the river mouth. Göta älv acts as wastewater recipient for several municipal WWTPs and the pathogens discharged with the wastewater effluent are transported downstream with the water flow. This means that Lärjeholm probably is the intake which receives most pathogens. Lärjeholm is also the largest raw water intake in Göta älv so a potential pathogen outbreak would cause most harm here. Moreover, as mentioned in Chapter 1, Göta älv is a particularly interesting study object when looking at preventive measures to reduce microbiological levels as it is one of the most affected water systems in Sweden.

3.2.1 Göta älv and Lärjeholm raw water intake

Göta älv is a 93 km long river which runs from the southern part of Lake Vänern down to the fjord of Älvsborg. The total drainage area covers 50 233 km^2 and the median water flow is approximately 550 m^3/s, though the flow varies between 300-900 m^3/s (Göta älvs vattenvårdsförbund, 2006). This makes it the largest watercourse in Sweden. Historically there have been many kinds of different activities along the river, such as industries, shipping, boatyards, agriculture, livestock keeping, wastewater discharge etc. Those activities affected and impaired the water quality for many years. However, during the 1970's active work with a variety of measures started and since then the quality has improved significantly.

Today the river serves as a surface raw water source for approximately 700 000 persons in the municipalities of Trollhättan, Vänersborg, Lilla Edet, Ale, Kungälv, Öckerö, Partille and Göteborg (Göta älvs vattenvårdsförbund, 2006). The largest raw water intake is Lärjeholm, which provides Göteborg municipality with approximately 170 000 m^3 drinking water every day. Each second 2 m^3 of water is collected at the intake and led to the two WTPs Alelyckan and Lackarebäck (Göteborg Stad, 2012a). It takes two to five days for the water to reach Lärjeholm from the outlet in Vänern.

The large number of drinking water consumers means that good raw water quality in Göta älv is essential from a health perspective. The intake in Lärjeholm has a water protection area that reaches from the intake up to the southern parts of Surte and has a total area of approximately 28 km^2. To further ensure a raw water of sufficient quality there are seven monitoring stations along the river which continuously control the water quality by analysis of e.g. pH, turbidity, conductivity and redox potential (Göteborgs Stad, 2011a). Faecal indicator organisms are also monitored continuously (Åström & Pettersson, 2007b). If the pathogen concentrations are too high, Lärjeholm raw water intake is closed (Göteborgs Stad, 2011a). For the definition of "too high pathogen concentrations" Göteborg municipality have chosen to keep the old raw water guideline values, see Table 1 in Section 2.1.1, as a basis for the local requirements for raw water (Friberg *et al*., 2010).

The microbial monitoring is especially important since Göta älv also acts as a recipient for discharge of treated wastewater from the WWTPs along the river as well as for microbiological loads from overflows, runoff and livestock farming (Göta Älvs Vattenvårdsförbund, 2007a). Between the outlet in Vänern and the raw water intake Lärjeholm, Göta älv receives wastewater from approximately 100 000 person equivalent (pe). About 95 % of this originates from municipal wastewater. Results

from Åström and Pettersson (2007b) shows that the microbiological content in the river correlate to the discharge of wastewater.

Thanks to the microbial monitoring in Göta älv, the raw water intake in Lärjeholm is able to close during peak concentrations of indicator organisms exceeding the guideline values, in order to avoid pathogens breaking through the WTPs (Göteborgs Stad, 2011a). During recent years the intake has been closed increasingly often. Since 2004 it has been closed almost one third of the year, whereof 73 % of the closing time was due to faecal impact, see Appendix 1. The combined closing time due to microbial impact was 72 days. The concentration of *E. coli* at Lärjeholm raw water intake during 2010 can be seen in Figure 14. In 2010 the closing time was only 64 days but 77 % was due to microbial contamination. The median *E. coli* concentration was 110 numbers/100 ml and the maximum detected concentration was 640 numbers/100 ml (Göta älvs vattenvårdsförbund, 2011) compared to the highest since 2004 which was 2800 numbers/100 ml in 2006 (Göta älvs vattenvårdsförbund, 2007).

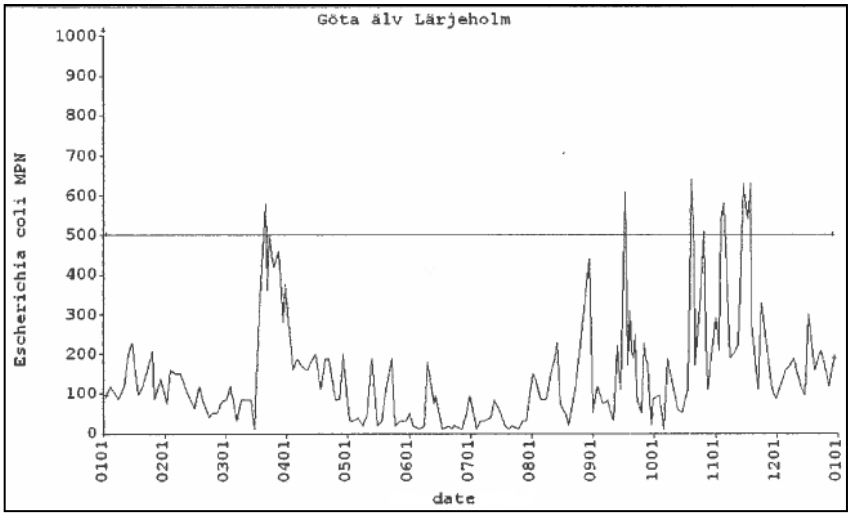

Figure 14 *E. coli concentrations at Lärjeholm raw water intake during 2010 with the guideline value marked with a horizontal line. (Göteborg Vatten, 2010) Published with permission.*

3.2.2 Inventory of WWTPs along Göta älv

An inventory of municipal wastewater treatment plants along Göta älv with discharge into the river has already been performed by Åström & Pettersson (2007b). It showed the amounts and portion of the total faecal load the municipalities of Vänersborg, Trollhättan, Lilla Edet, Ale and Kungälv have discharged into Göta älv. There are a total of eight WWTPs in these municipalities which affects Göteborgs raw water intake in Lärjeholm, see Figure 15.

Figure 15 *Locations of the eight WWTPs with discharge to Göta älv upstream of Lärjeholm. Modified picture from Eniro.se*

The treatment process at all WWTPs is conventional and consists of mechanical, biological and chemical steps, although the actual treatment processes varies. The stricter discharge limits, particularly for biological oxygen demand (BOD), phosphorus and nitrogen, has made it difficult for many of the WWTPs to meet the targets. Therefore, upgrades and improvements are ongoing or at a planning stage for several of the WWTPs.

To get more recent effluent data the inventory result from Åström & Pettersson (2007b) have been updated through contact with the concerned municipalities. Discharge volumes from 2011 and distance to Lärjeholm for each plant were gathered. The most recent information regarding person equivalent and annual outflow are presented in Table 7, including the distances from the WWTPs to the intake in Lärjeholm. The distances were quantified by a measurement feature on internet (eniro.se).

Table 7 *Results from inventory of WWTPs along Göta älv.*

Municipality	WWTP	People connected (pe)	Outflow, annual (1000 m^3)	Outflow, annual mean (m^3/s)	Approx. distance to Lärjeholm (km)
Kungälv	Diseröd	1 278 [a]	153 [b]	0.00486	18
Ale	Älvängen	5 923 [a]	1 136 [c]	0.03602	24
Lilla Edet	Lödöse	1 600 [a]	253 [d *]	0.00803	33
	Nygård	400 [a]	52 [d *]	0.00165	38
	Ellbo	6 208 [a]	871 [d]	0.02762	49
	Hjärtum	400 [a]	96 [d]	0.00305	56
Trollhättan	Arvidstorp	50 000 [a]	11 670 [e]	0.37005	70
Vänersborg	Holmängen	27 230 [a]	6 167 [f]	0.19555	85

[a] Göta Älvs vattenvårdsförbund (2007a)
[b] Jan-Åke Ambjörnsson, VA-verket, Kungälv kommun, e-mail 20120426
[c] Anja Pielström, Sektor samhällsbyggnad, Ale kommun, e-mail 20120221
[d] Göran Åberg, Tekniker, Lilla Edets kommun, e-mail 20120508
[e] Trollhättan Energi (2012). *Miljörapport 2011 Arvidstorps reningsverk*. Trollhättan kommun
[f] KatarinaEnbom, Driftschef, VA-verket, Vänersborgs kommun, e-mail 20120228
[*] During some months in autumn 2011the flow was estimated due to problems measuring the flow.

Data about concentrations of microbiological parameters in the effluent from the WWTPs was also required for the risk assessment. However, effluent data regarding microbial content is not standard for the monitoring at WWTPs in Sweden and was therefore not available for most of the plants. The exception was Arvidstorp WWTP in Trollhättan which is involved in an EU research project, called VISK. The VISK project is aiming to decrease the vulnerability of waterborne virus infections in the society. As a part of this project systematic analyses of the concentration of a range of microorganisms in inlet and outlet at Arvidstorp WWTP have been carried out (VISK, 2012).

Effluent data from between June 2011 and January 2012 for a few common indicator organisms were available. Data for concentrations of specific pathogens were though not available from the VISK measurements. However, since coliphages is a good indicator organism for virus and *Clostridium Perfringens* is a good indicator organism for protozoa in treatment processes removal efficiencies of coliphages and *Clostridium Perfringens* from Arvidstorp WWTP were assumed to be similar to removal efficiencies for *Cryptosporidium* and *Norovirus* at all the WWTPs along Göta älv. By assuming that the typical concentrations of *Cryptosporidium* and *Norovirus* in Swedish raw wastewater from Table 2, Section 2.2.1.1 also were applicable for the WWTPs along Göta älv, the effluent concentrations of *Cryptosporidium* and *Norovirus* from the WWTPs could be calculated. These calculations can be seen in Appendix 2. The result from this is presented in Table 8.

To assume that the values from Arvidstorp were applicable for all WWTPs along Göta älv is a reasonable assumption as it is close geographically and similar consumption patterns and habits among the population are likely. Some differences could though be assumed due to differences in distribution system, relationship in household/industry relationship and treatment processes.

The effluent concentration of microorganisms that were used in the risk assessment can be seen in Table 8. The concentrations of *E. coli*, Enterococci and Total coliforms were obtained from the VISK measurements while *Cryptosporidium* and *Norovirus* were estimated as described above.

Table 8 *Estimated concentrations of microorganisms in effluent from the WWTPs.*

Microorganism	Concentration	StDev (%)
E. coli	62 005 cfu/100ml	1.0
Enterococci	119 061 cfu/100ml	2.7
Total coliforms	618 647 cfu/100ml	1.8
Cryptosporidium	1.816 numbers/100ml	0.9 [a]
Norovirus	149.645 numbers/100ml	0.6 [b]

[a] Standard deviation from measurements of *Clostridium Perfringens*
[b] Standard deviation from measurements of coliphages

3.2.3 Inventory of Alelyckan WTP

An inventory of the drinking water treatment plant Alelyckan was performed to quantify the risks reduction potential for drinking water consumers in Göteborg municipality by installing disc filters at all WWTP along Göta älv. The aim was to identify the involved treatment processes and the levels of removal. Other general information of the conditions in the plant was also gathered. The inventory was performed by a literature study of reported data.

Alelyckan WTP has conventional drinking water treatment consisting of coagulation, flocculation, sedimentation and filtration. There is 6 parallel treatment lines (Lindhe *et al.*, 2008).When the water from Göta älv enters the WTP it first passes ice- and oil screens together with a coarse grid followed by a finer grid. After the first granular separation, lime is used to adjust the pH of the water to pH 9.5-10.0. This is to facilitate and accelerate the following chemical precipitation. Aluminum sulphate is added in the following flocculation basins where the water is slowly stirred for about 30 minutes. This lowers the pH again to around 6.5. The water then enters the sedimention basins where the formed flocs get the opportunity to settle. To remove all flocs, the water also needs to be filtered. A rapid granulated activated carbon filter is used. Before distribution of the treated water the pH is adjusted to 8 by adding lime. Also the hardness and alkalinity are adjusted by adding sodium hydroxide and carbon dioxide (CO). Finally the water is disinfected by a small dose of a mix of chlorine and

chlorine dioxide. The total time from when the water enters the plant to ready drinking water takes normally around 7 hours. (Göteborg Stad, 2011b) After treatment the water is delivered to the consumers. The delivery time is up to two days, depending on the distance from the WTP.

In Table 9 the Log_{10} reductions for conventional treatment which were assumed to be applicable for Alelyckan are presented. They were based on the values from Smeets (2006) which were decreased by 15 % to be on the safe side. The maximum chlorine concentration in drinking water is 0.4 mg/l (Livsmedelsverket, 2011) but the concentration decreases rapidly in the beginning, why higher concentrations normally are added. When a mix of chlorine and chlorine dioxide is added, the first rapid decrease is smaller. Therefore doses of 0.5 mg/l were assumed for the chlorination at Alelyckan. The temperature varies between seasons, but the median temperature in 2011 of 10.6 °C was used (Göteborg Stad, 2012b).

Table 9 *Log_{10} reductions for conventional treatment (coagulation-flocculation-sedimentation-filtration).*

Microorganism	Log_{10} reductions		
	Mean	Min	Max
Bacteria	1.8	0.9	2.9
Viruses	2.6	1.0	4.5
Cryptosporidium	2.7	1.2	4.7

3.2.4 Quantification of the risk reduction potential

The peaks of faecal contamination in the raw water can be described as a function of a baseline level, caused mainly by discharges from normal operation of WWTPs, and peaks due to various events upstream that are added upon the baseline . By decreasing this baseline, the peaks will be decreased equally. This could potentially mean that the targets at the raw water intake are met more days of the year, which is the desired outcome of this risk study.

The risk reduction potential from reducing the baseline concentration was quantified as decrease in indicator organism and pathogen concentration at Lärjeholm raw water intake as well as decrease in disease cases among the drinking water consumers in Göteborg municipality.

3.2.5 Parameters

The reduction in microorganism concentrations at Lärjeholm was estimated for *E. coli*, enterococci, total coliforms, *Norovirus* and *Cryptosporidium*. For the reduction of the risks for the consumers focused on *EHEC*, *Norovirus* and *Cryptosporidium*. *EHEC* was chosen as it is a pathogenic strain of *E. coli* and therefore could pose a risk to humans in contrast to *E. coli* in general. The choice of

indicator organisms/pathogens was also based on what microorganisms that were possible to select in the QMRA programme used for the risk assessment.

3.2.6 Assessment procedure

The expected concentrations of microorganisms at Lärjeholm raw water intake was calculated both for the present discharge concentrations and for the future discharge scenario based on all WWTPs along Göta älv installing disc filters with the measured removal efficiency. The difference between these two scenarios provided the possible decrease of the baseline concentration of pathogens in Göta älv. Based on the theory that use of coagulation/flocculation will create larger more stable particles in the wastewater and improve the removal efficiency of microorganisms, additional future scenarios with 70, 80, 90 and 99 % removal efficiency were also studied. The future scenarios can be applied to disc filter facilities with coagulation/flocculation as a pre-treatment step to get an estimation of the risk reduction potential when investigations of the removal efficiency of such facilities have been performed. All the studied scenarios can be seen in Table 10.

Table 10 *Scenarios for which the risk reduction potential was studied.*

Scenario	Description
0	Present discharge from WWTPs
1	Discharge after installation of disc filters with measured removal efficiency
2	Discharge after installation of disc filters with 70 % removal efficiency
3	Discharge after installation of disc filters with 80 % removal efficiency
4	Discharge after installation of disc filters with 90 % removal efficiency
5	Discharge after installation of disc filters with 99 % removal efficiency

The calculations of expected raw water concentrations were carried out using spreadsheet in combination with the statistical distribution application software *Oracle Crystal Ball*, which allows including probability distributions for the input data using Monte Carlo simulations. It also allowed sensitivity analysis of the uncertain parameters. Input data were extracted from the inventory of the WWTPs, see Section 3.2.2. The expected concentration from the discharge from the WWTPs for the microorganisms at Lärjeholm ($C_{Lärjeholm}$) was calculated as the sum of the outflow from all WWTPs ($F_{effluentWWTP}$) times the assumed concentration of the microorganism in the effluent ($C_{effluentWWTP}$) divided by the median water flow in Göta älv ($F_{Götaälv}$), see Equation 2.

$$C_{Lärjeholm} = \frac{\sum (F_{effluentWWTP}) \times C_{effluentWWTP}}{F_{Götaälv}} \qquad [2]$$

This simplified calculation assumes total mixing and no inactivation of the microorganisms. It is assumed that total mixing of the effluent wastewater with the river water in Göta älv occur within 10 km of the effluent points of the WWTPs. As all WWTPs are located at a distance larger than 10 km upstream he raw water intake, it is not necessary to take the distances between effluent point and the intake into consideration in the calculations.

As the mean annual temperature in Swedish waters is relatively low, most microorganisms should have long inactivation time in Göta älv. This also makes it reasonable to neglect the inactivation of pathogens during the short time it takes for the water and faecal microorganisms to reach Lärjeholm raw water intake. It could though result in a slight overestimation of the concentrations at the intake but the same magnitude of overestimation should be present for all scenarios, why the reduction in baseline concentration should be the same.

For the flow variables above, triangular distributions were assumed. For $F_{effluent\ WWTP}$, the likeliest value was given by the average outflow per second based on the annual effluent of the plants. The minimum and maximum were assumed to be ±15 % of the average. The likeliest value for $F_{Göta\ älv}$ was given by the median water flow and minimum and maximum were given by the minimum and maximum measured average flows in the river. For $C_{effluent\ WWTP}$ a normal distribution was assumed as the uncertainty is connected to errors in measurements. The mean and standard deviations were given by measured average concentrations and the difference in removal between the different sampling situations described in Section 3.1.3 and 3.1.4.

The calculated decrease in concentration of *E. coli* at Lärjeholm was compared to the diagram of *E. coli* concentration during 2010, see Figure 14 in Section 3.2.1, to get an indication of whether the decrease would be sufficient to keep the raw water levels within the guideline values more days of the year.

From the concentrations at the raw water intake it was then calculated how many people would be infected due to the pathogens passing through Göteborgs drinking water treatment plant Alelyckan for each scenario. For *EHEC*, the concentration of *E. coli* at the intake was used. The probability of infection was calculated using a Swedish Microbiological Risk Assessment (MRA) model developed within a by the Swedish Water Association founded research project (Lundberg Abrahamsson *et al*. 2009) for the modelling programme *Analytica*. MRA is a Swedish version of Quantitative Microbial Risk Assessment (QMRA) and the model is developed for Swedish conditions in drinking water production. The model facilitates calculation of pathogen reduction through a treatment plant which otherwise requires considerable knowledge of treatment processes, raw water quality, infectivity of different pathogens, response to treatment and dose-response relationship. It also allows including probability distributions functions of input data. (Svenskt Vatten, 2012). Input data for the treatment processes was extracted from the results of the inventory of Alelyckan (Section 3.2.3).

Triangular distribution was assumed for the conventional treatment step. The likeliest value was given by the average removal in Table 9. The travel time of the treated water to consumer was assumed to be 15 min.

The difference in probability of infection between the future scenarios and the present scenario provided the risk reduction potential by installing disc filters at all upstream

WWTPs for the consumers in Göteborg municipality. As many of the parameters are associated with uncertainty, a sensitivity analysis was also carried out.

4 Results

First the results of the general wastewater treatment parameters are presented to give a picture of the conditions during the sampling compared to other studies. Then the removal efficiencies is presented followed by the results from the risk assessment.

4.1 General parameters

The total removal efficiency of particles from the momentary grab samples taken on the 8 March was between 88-96 %, see Table 11, with slightly higher removal in the filter feed from PD. This is in line with expectations as particle size distribution showed that this water contained more large particles, see Appendix 3. The differences in size distribution between SS and PD are consistent with results presented by Yimamu (2012).

From the particle distribution it can also be observed that not all particles larger than the disc filter pore size of 15 µm were removed. Possible reasons for this result could be that particles have different lengths in different dimensions, or flocculation of smaller particles after the filtration. That small particles flocculate into larger ones after filtration is also supported by the fact that particles in the size range of 10-15 µm appear to be separated even though they are smaller than the pore openings. However, these particles could also to some degree be separated due to clogging of the filter cloth, which reduce the pore size.

Moreover, a higher content in the effluent than in the influent of the smallest particles can be seen. This indicates that larger particles to some degree are broken down into smaller within the filter. Similar results like these have also been seen in earlier investigations (Yimamu, 2012 & Behzadirad, 2010).

Table 11 *Removal efficiency of particles during the first sampling period.*

Particles	Influent (μm^3)	Effluent (μm^3)	Separated particles (μm^3)	Removed particle volume (%)
Disc filter, feed from SS	$7.8 \cdot 10^{-6}$	$0.9 \cdot 10^{-6}$	$6.9 \cdot 10^{-6}$	88.5
feed from PD	$22.4 \cdot 10^{-6}$	$0.8 \cdot 10^{-6}$	$21.5 \cdot 10^{-6}$	96.2

The measurements of suspended solids showed an average removal of suspended solids of 82.1 % for the period 6-8 March and 93.3 % for the period 29-31 May based on the continuous measurements of water parameters by Gryaab and 78.5 % based on the 1h composite sample taken 8 March over the entire disc filter facility, see Table 12. This indicates slightly higher removal efficiency during the summer months. Also in the study by Yimamu (2012), a slight increase of removal efficiency of particles could be detected for the summer months, though the removal efficiency was virtually the same over the year. Another explanation for the higher removal in the second

sampling round could be that the effective pore size could have been smaller as the biofilm had had more time to build up since the last acid cleaning. The removal is higher compared to other previous studies (Behzadirad, 2010 & Yimamu, 2012)

Table 12 *Removal efficiency of suspended solids during sampling.*

Sample type	Influent (mg/l)	Effluent (mg/l)	Separated suspended solids (mg/l)	Removed suspended solids volume (%)
Continuous (6-8 March)	17.59	3.14	14.44	82.1
1h composite (8 March)	16.29	3.50	12.79	78.5
Continuous (29-31 May)	17.74	1.20	16.54	93.3

The 1h composite grab samples from 8 March of P_{tot} and N_{tot} showed a removal efficiency of P_{tot} of 59.6 % and a removal efficiency of N_{tot} of 17.9 %, see Table 13. The removal efficiency and the effluent concentration of P_{tot} seem to lie in the normal range compared to previous studies at Rya WWTP (Behzadirad, 2010 & Yimamu, 2012). Both the removal efficiency and the effluent concentration of N_{tot} are higher than in previous investigations. Lower removal efficiency of N_{tot} is lower than for P_{tot} is expected as disc filters not are designed for nitrogen removal primarily.

Table 13 *Removal efficiency of P_{tot} and N_{tot} during sampling.*

Sample type	Influent (mg/l)	Effluent (mg/l)	Separated content (mg/l)	Removed content volume (%)
1h composite - P_{tot} (8 March)	0.35	0.14	0.21	59.6
1h composite - N_{tot} (8 March)	9.40	7.72	1.68	17.9

To conclude, the concentration of different components in the wastewater and the removal efficiencies of these components vary substantially. The result regarding particles, suspended solid, P_{tot} and N_{tot} on the sampling days appear though to have been relatively reasonable compared to previous measurements at Rya WWTP around the same time of the year.

4.2 Removal efficiency of microorganisms in disc filters

The concentrations of indicator organisms and *Norovirus* in the samples can be seen in Appendix 4 for sampling period one and in Appendix 5 for sampling period two. The standard deviations of the triplicate samples taken during sampling one are generally large, varying between 3.5-47 %.

A logarithmic presentation of the average concentrations of indicator bacteria in each disc filter units and over the entire disc filter facility from the first sampling can be seen in Figure 16. Generally, it can be said that the influent from the PD consistently contains lower concentrations of all three indicator organisms than the influent from the SS. Also the second sampling showed lower concentrations of indicator bacteria in the water from PD. As expected the concentrations of total coliforms is above the concentrations of *E. coli* and enterococci, except for the composite samples gathered over the filter feed from PD.

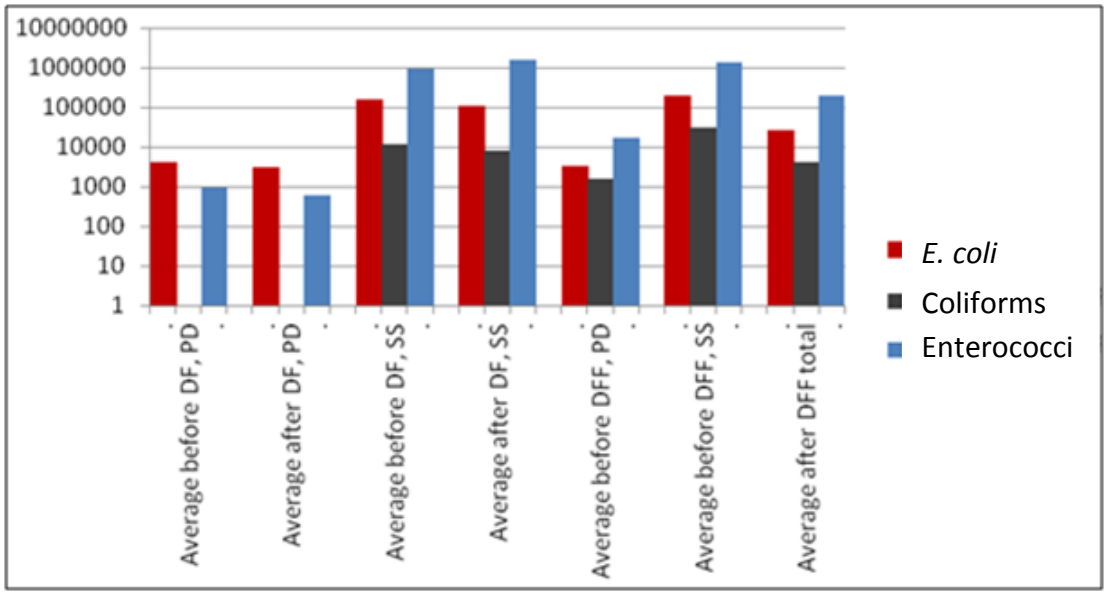

Figure 16 *Comparison between the average concentrations in the individual disc filter units (DF)receiving water from PD and SS respectively and over the disc filter facility (DFF).*

The average removal efficiencies of *E. coli*, enterococci and total coliforms for the two disc filters and the entire disc filter facility can be seen in Tables 14-16.

Large differences in removal efficiencies between the different sampling situations can be seen. The efficiency varies between -72.0-81.8 %. Negative removal percentages are observed in three cases; for *E. coli* in the momentary grab samples in the filter feed from SS and in the second 24h composite measurement in the filter feed from SS as well as for total coliforms in the 24h composite measurement in the filter feed from SS.

As a result of the large standard deviations of the measured concentrations, the standard deviation of the removal efficiency is also large. However, if disregarding the negative values, some relations between the removal efficiencies can be derived from Tables 14-16. The removal efficiency is similar for the different types of indicator bacteria. Also, the removal efficiencies of indicator bacteria over the entire

disc filter facility are in the same size range as for the momentary samples over single disc filters, in the range of 65-80 %. The composite samples from the first sampling show lower removal efficiency between 25-36 %. No apparent differences in removal efficiency between the disc filter feed from PD and the filter feed from SS can be seen. It can though be observed that the standard deviation is larger for filter feed from PD. This could be due to this water containing fewer but larger particles which could cause homogenisation problems of the water samples. The composite samples of *E. coli* from the second sampling show a removal of 64.3 % for filter feed from PD and -7.1 % for filter feed from SS, i.e. both higher and lower removal efficiency than in the first sampling. However, the average of these is 28 %, which is in the same region as in the first sampling.

Table 14 *Removal efficiency for E. coli for the three locations measured; disc filters feed from PD and SS respectively and the entire disc filter facility. The composite samples are marked (1) and (2) as representation of sampling period one (6-8 March) and two (29-31 March) respectively.*

Location	Removed *E. coli* (numbers/100ml)	Removal efficiency (%)	StDev (%)
PD (1), *composite 24h*	1033	25.6	50.4
SS (1), *composite 24h*	52667	32.2	17.5
PD (2), *composite 24h*	900	64.3	-
SS (2), *composite 24h*	-1000	-7.1	-
PD, *momentary grab sample*	3300	66.0	-
SS, *momentary grab sample*	-40000	-33.3	-
Entire disc filter facility	51923	66.4	30.8

Table 15 *Removal efficiency for enterococci for the three locations measured; disc filters feed from PD and SS respectively and the entire disc filter facility.*

Location	Removed enteroccoci (cfu/100ml)	Removal efficiency (%)	StDev (%)
PD, *composite 24h*	-	-	-
SS, *composite 24h*	3967	33.1	25.6
PD, *momentary grab sample*	<2000	66.7	-
SS, *momentary grab sample*	32700	81.8	-
Entire disc filter facility	8626	67.4	55.8

Table 16 *Removal efficiency for total coliforms for the three locations measured; disc filters feed from PD and SS respectively and the entire disc filter facility.*

Location	Removed total coliforms (numbers/100ml)	Removal efficiency (%)	StDev (%)
PD, *composite 24h*	337	36.1	51.0
SS, *composite 24h*	-670000	-72.0	13.0
PD, *momentary grab sample*	26400	80.0	-
SS, *momentary grab sample*	-	-	-
Entire disc filter facility	368529	65.6	25.9

The average removal efficiencies of coliphages and *Clostridium Perfringens* measured over two separate disc filters during the second sampling 29-31 May can be seen in Table 17.

The result show a removal of *Clostridium Perfringens* of 79.7 % for the filter feed from PD and 17.4 % for the filter feed from SS. For coliphages it shows large negative removal efficiency. This is interesting as coliphage removal is an indicator of *Norovirus* removal.

Table 17 *Removal efficiency for coliphages and Clostridium Perfringens for the disc filter feed from PD and SS respectively.*

Location	Removed Coliphages (pfu/100ml)	Removal efficiency (%)	Removed *Clostridium Perfringens* (cfu/100ml)	Removal efficiency (%)
Disc filter PD, *composite*	-6000	-66.7	3030	79.7
Disc filter SS, *composite*	-14000	-100.0	400	17.4

The measured removal efficiencies of *Norovirus* over disc filters can be seen in Table 18. Both samplings resulted in largely negative removals. As negative removal is unlikely in the disc filters, these values are probably connected to some type of error and should be treated with caution. Possible sources of error in this case are discussed in Section 5.1.

Table 18 *Removal efficiency for Norovirus for the disc filter feed from PD and SS respectively.*

Location	Removal efficiency *Norovirus* (GI) (%)	Removal efficiency *Norovirus* (GII) (%)
Average (1)	-45,7	-41,7
Average (2)	-141,5	-246,4

To summarize, the result is connected to large standard deviations and the result between the momentary and composite samples as well as between the first and the second sampling differ.

An average removal efficiency of all the sampling situations can be seen in Table 19. Norovirus and its indicator shows large negative removal so no risk reduction is possible to calculated for those. The removal efficiencies of the other larger microorganisms are 27-62 %. This is low compared to other barriers for microbiological organisms, which as mentioned not uncommonly remove between 80-99.9 %. In comparison sand filters remove up to 98.9-99.9 % of pathogens.

Enterococci have the largest removal efficiency. It was though the only microorganism which did not have any negative removal efficiencies that could influence the average removal. However, a few of the samples analysed for enerococci was disregarded by the laboratory personnel as dilution problems was suspected. This means that the result for enterococci is more uncertain. *Clostridium Perfringens* have the second highest removal efficiency. That *Clostridium Perfringens* have the highest removal efficiency could be expected since it is the largest in terms of size.

Table 19 *Average removal efficiencies.*

	E. coli	Enterococci	Total coliforms	*Clostridium Perfringens*	*Coliphages*	*Norovirus*
Average removal efficiency	31 %	62 %	27 %	48 %	-83 %	-119 %

4.3 Risk reduction potential

The output results of annual risk of infection from the MRA can be seen in Appendix 6. The calculated most probable concentrations (MPC) at Lärjeholm raw water intake as well as 5^{th}-percentile, median and 95^{th}-percentileconcentrations for the present discharge of pathogens from the upstream WWTPs (Scenario 0) can be seen in Table 20.

In Table 20 it can be seen that the MPC for all indicator bacteria is below the raw water guidelines. The values are 15-28 % of the maximum allowed values. For the 95th percentile concentration of intestinal enterococci from wastewater effluent alone is not far from exceeding the guideline value. Both protozoa and *Norovirus* are present in small concentrations, though the guideline here is that neither should be detected.

The present concentrations at the raw water intake correspond to an annual risk of infection due to secondary wastewater effluent for the drinking water consumers of $4.8 \cdot 10^{-4}$ due to *Norovirus* and of $3.9 \cdot 10^{-3}$ due to *Cryptosporidium*. These risks are above the acceptable health risk according to U.S. EPA health target risk of 10^{-4}. There is no risk for the consumers of *EHEC* infection as long as the drinking plant works properly with this *E. coli* concentration at the intake. That means there is no risk reducing potential of *EHEC* during normal operation.

When studying the values in Table 20, it should be remembered that the concentration from the WWTPs only is a part of the total concentration at the raw water intake. Comparing the calculated median of *E. coli* (68.7 numbers/100 ml) for the present discharge with the measured median of *E. coli* in 2010 (110 numbers/100 ml), it seems that the discharge from the upstream WWTPs contributes with somewhere in the region of 62 % of the baseline concentration in Göta älv. This confirms that municipal wastewater effluent is the major pathogen source for Göta älv.

Table 20 *Present calculated baseline concentrations of microorganisms at Lärjeholm from WWTPs' discharges to Göta älv (Scenario 0).*

Value	*E. coli* (numbers/ 100ml)	Enterococci (cfu/100ml)	Total coliforms (numbers/ 100ml)	*Norovirus* (numbers/ 100ml)	*Cryptosporidium* (numbers/ 100ml)
MPC	72.9	140	728	0.176	0.002
median	68.7	196	835	0.167	0.002
5 %	23.2	55.6	257	0.091	0.001
95 %	132	437	1800	0.286	0.004

After installation of disc filters at all WWTPs, the concentration will decrease in proportion to the calculated removal efficiency. The expected concentrations for Scenario 1 are presented in Table 21. These concentrations at the Lärjeholm relate to an annual risk of infection for the drinking water consumers of $2.3 \cdot 10^{-3}$ due to *Cryptosporidium*, which still exceeds the health target.

Table 21 *Calculated concentrations of microorganisms from WWTPs at Lärjeholm for Scenario 1.*

Value	*E. coli* (numbers/ 100ml)	Enterococci (cfu/100ml)	Total coliforms (numbers/ 100ml)	*Norovirus* (numbers/ 100ml)	*Cryptosporidium* (numbers/ 100ml)
MPC	50.3	53.2	531		0.001
median	42.3	61.5	518		0.001
5 %	2.00	0	0		0
95 %	121	265	2090		0.003

The average decrease of baseline concentration and the average risk reduction for the drinking water consumers in Göteborg municipality between Scenario 0 and Scenario 1 is presented in Table 22. The concentration is decreased by 22.6 *E. coli*/100 ml and 0.001 *Cryptosporidium*/100 ml at Lärjeholm.

If the decrease of *E. coli* is compared to the diagram in Figure 14, it is seen that this decrease will only help meeting the guideline value for a few days. The major peaks will never be possible to decrease below the guideline limit as the *E. coli* from the WWTPs is less than the amount of *E. coli* that exceeds limit.

The risk for *Cryptosporidium* infection for the drinking water consumers in Göteborg is decreased by $1.6 \cdot 10^{-3}$ per year, which means 836 less infections annually. However, for the 95th-procentile it would be in excess of 12900 less infections.

Table 22 *The decrease in average concentration and the risk reduction for the drinking water consumers in Göteborg municipality if disc filters are installed at all upstream WWTPs.*

Risk reduction quantification	*EHEC*	*Norovirus*	*Cryptosporidium*
Decrease in concentration, mean	22.6 numbers/100ml		0.001 numbers/100ml
Decrease in risk for consumers, mean	No risk		$1.6 \cdot 10^{-3}$
Decrease in risk for consumers, 95%-ile	No risk		$2.5 \cdot 10^{-2}$

The most probable concentrations (MPC) at Lärjeholm raw water intake for the future Scenarios 2-5 can be seen in Table 23. The 5th-procentile and 95th-procentile are presented in brackets. The higher removal efficiency, the lower concentration at Lärjeholm raw water intake could be expected.

The annual risk for the drinking water consumers in Göteborg due to wastewater effluent for each of the future scenarios are presented in Table 24. From the table it can be seen that a removal efficiency of 80 % would be sufficient to reduce the risk below acceptable levels for *Norovirus* whereas a removal efficiency of 99 % would be needed for *Cryptosporidium*.

Table 23 Calculated expected concentrations at the raw water intake in Lärjeholm for the four future scenarios, Scenario 2-5, given by MPC and (5%-ile; 95%-ile).

Future scenario	*E. coli* (numbers/ 100ml)	Enterococci (cfu/100ml)	Coliforms (numbers/ 100ml)	*Norovirus* (numbers/ 100ml)	*Cryptosporidium* (numbers/ 100ml)
2 (-70 %)	21.9 (7.0; 39.7)	42.0 (16.7; 130.9)	218.3 (77.0; 541.3)	0.0528 (0.0272; 0.0857)	0.0006 (0.0002; 0.0011)
3 (-80 %)	14.6 (4.6; 26.4)	28.0 (11.1; 87.3)	145.5 (51.4; 360.9)	0.0352 (0.0181; 0.0571)	0.0004 (0.0002; 0.0008)
4 (-90 %)	7.3 (2.3; 13.2)	14.0 (5.6; 43.6)	72.8 (25.7; 180.4)	0.0176 (0.0091; 0.0286)	0.0002 (0.0001; 0.0004)
5 (-99 %)	0.7 (0.2; 1.3)	1.4 (0.6; 4.4)	7.3 (2.6; 18.0)	0.0018 (0.0009;0.0029)	0.00002 (0.00001;0.00004)

Table 24 *The risk for the drinking water consumers in Göteborg for each scenario.*

Future scenario	*EHEC* (numbers/100ml)	*Norovirus* (numbers/100ml)	Protozoa (numbers/100ml)
2 (-70 %)	0	$1.43 \cdot 10^{-04}$	$1.11 \cdot 10^{-03}$
3 (-80 %)	0	$9.63 \cdot 10^{-05}$	$8.28 \cdot 10^{-04}$
4 (-90 %)	0	$4.78 \cdot 10^{-05}$	$4.15 \cdot 10^{-04}$
5 (-99 %)	0	$4.81 \cdot 10^{-06}$	$4.11 \cdot 10^{-05}$

4.4 Sensitivity analysis

For the present discharge from the WWTPs the major factor influencing the concentration at Lärjeholm raw water intake is the concentration in the secondary wastewater effluent of the microorganism in question. The second most important factor is the flow in Göta älv. The sensitivity for *E. coli* in Scenario 0 can be seen in Figure 17. The sensitivity was similar for the other microorganisms.

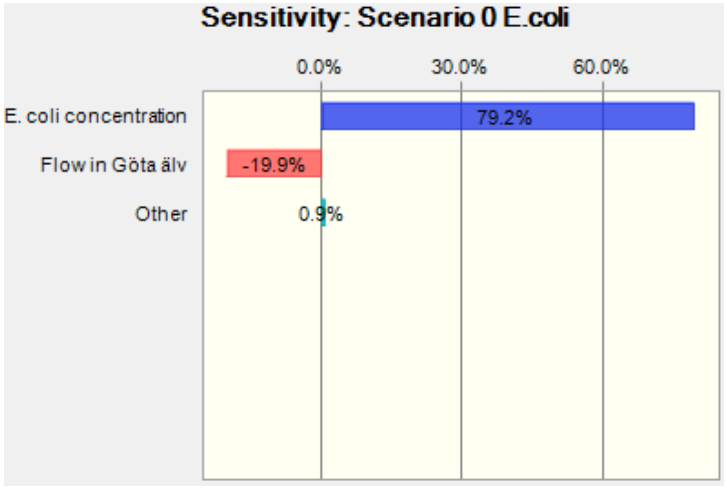

Figure 17 *The sensitivity for E. coli for Scenario 0.*

The concentration at Lärjeholm raw water intake for the future scenario that all WWTPs install disc filters with the measured removal efficiency (Scenario 1) is mainly influenced by the large uncertainties in the measurement result, followed by the concentration in the secondary wastewater effluent of the microorganism in question and then the flow in Göta älv. The sensitivity for *E. coli* in scenario 1 can be seen in Figure 18. Again the sensitivity was similar for the other microorganisms.

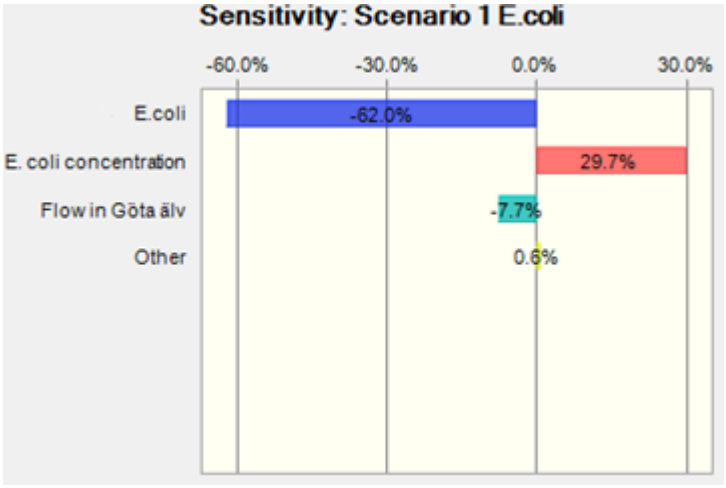

Figure 18 *The sensitivity for E. coli for Scenario 1.*

5 Discussion

Many factors and conditions influence the results and therefore they need to be properly evaluated to be able to draw conclusions of the removal efficiency and risk reduction potential. In this chapter the method and the choices made in the planning phase are evaluated regarding suitability and whether appropriate assumptions have been made. Also the results are analysed and evaluated in terms of reliability and credibility.

5.1 Choice of sampling method

There are many factors that influence the ability of disc filters to remove pathogenic microorganisms. Many of these vary over the day, month or year, such as suspended solids and pathogenic content in the incoming water, ability of the pathogens to attach to particles, particle sizes and biofilm build-up on the filter cloths. The sampling was only performed at two occasions, March and May. Using composite samplers for 24 h periods should cover variations over the day to some extent. However, variations over longer periods were not covered by this sampling method and therefore, it will not give a fair picture of the average removal efficiency over the whole year. More samples taken during a longer time period would have given a better picture of the average annual removal efficiency as it would have covered more of the varying factors. Preferably, samples should have been taken over a whole year. This was unfortunately not possible to carry through due to time and cost restrains.

Additional sampling occasions could have been carried out if triplicate samples had not been taken during the first sampling. However, the few more sampling occasions that should have been possible would only give a slightly better approximation of the annual removal efficiency. The downside of excluding triplicate sample analysis is that nothing could have been said about the certainty of the analysis method. It was considered more important to evaluate the certainty of the results given the few sampling occasions.

To compensate for the lack of sampling occasions the results of the general parameters were compared to previous more extensive measurements of general parameters at Rya WWTP (Yimamu, 2012 & Behzadirad, 2010). By doing this the result could be put in relation to general performance of the filters and the performance during the sampling period could be related to the annual removal efficiency. Though a small increase in removal of suspended particles could be distinguished during the summer months, the level of removal efficiency is relatively uniform during the year. The removal of suspended solids during the sampling was also higher than comparable removal ranges from other studies which indicate that the removal of microorganisms during this time also should be better than normal. Also, no distinct differences can be seen in removal of microorganisms between the two sampling occasions. Hence, it is not likely that the removal of pathogens will vary substantially from the presented results.

One thing that could have been done to get more accurate removal efficiency over the year would be to consider average biofilm build-up also during the first sampling period. As the situation was, the disc filters were newly cleaned during the first sampling (6-8 March). This was considered good as it would mean exactly equal filter conditions to be granted. However, if the biofilm build-up has considerable impact on

the removal, this would give lower removal efficiency than average since less biofilm would mean larger pore openings.

The time for the sampling was chosen considering what time the probability of detecting *Norovirus* would be high. It was successful since *Norovirus* indeed was detected in very high concentrations. The PCR-analysis is less accurate for concentrations under the detection limit of 50 000 *Norovirus*/litre (Nordgren *et al.*, 2009). However, the measured concentrations of *Norovirus* are well above the detection limit and thereby it should not be the reason for the negative removal efficiency.

Nevertheless, this unexpected result could possibly be related to the analysis method. Nordgren *et al*. (2009) discusses the PCR analysis method applied for *Norovirus*. They found indications that analysis of wastewater with higher density of particles generally resulted in fewer viruses being detected. The reason was thought to be due to viral attachment to the particles. As some of the particles are removed in the first low speed centrifugation before the RNA extraction, viruses attached to these will not be counted. More particles could also mean risk for clogging the membranes. Since the influent contains approximately 80-90 % more suspended solids than the effluent it is possible that fewer of the viruses in the influent were detected than for the effluent water. This could affect the results considerably. Moreover, the particle analysis showed that some of the larger particles in the influent were broken into smaller particles within the filter. This event could release viruses attached to the particle so that more free viruses are released and further contribute to higher concentration of virus in the effluent than in the influent.. The analysis method may therefore not be appropriate for this type of analysis.

The analyses of indicator organisms of the sampled water are connected to high uncertainty. In some samples, the concentration of indicator organisms were under normal concentration levels, why these data was disregarded by the laboratory personnel, as dilution error was suspected. For the samples that were reported the standard deviation was up to 56 %.

Other sources of uncertainty, except for the analysis, are for example human mistakes, problem with homogenisation of samples and effects from transport and storage of the samples before analysis. Wilén *et al.* (2012) discusses the problem to homogenise wastewater sample and that the used analysis methods possibly may not be appropriate for samples containing high amounts of particles. The difficulty to homogenise the samples probably contributed to the high uncertainties connected to the result as a particle containing large amounts of microorganisms in one sample could affect the result substantially for the analyses methods used for indicator analysis.

Moreover, during the period of the continuous measurements some technical problems occurred. For one hour on 7 March there was a power outage which caused a stop of the water flow through the disc filter. This resulted in the same water being sampled twice during the continuous measurements of the disc filter feed from SS. No specific effect from this incident could be detected in the results but it could still be a source of error.

5.2 Removal efficiency and factors influencing the result

The measurements showed removal efficiencies in the range of 27-62 %. That is to be considered quite low compared to many other treatment processes. For slow and rapid sand filters, which as mentioned earlier also are common tertiary treatment steps, studies have showed removal efficiencies of microorganisms of up to 90-99.9 %. However, for rapid sand filter this high removal efficiency is for coagulation/flocculation prior to filtration. Without it, the efficiency dropped to 25 % in the study by Koivunen *et al*. (2002). As rapid sand filters is a physical removal process just like disc filters, this indicates the importance of coagulation/flocculation for such processes. It could be expected that coagulation/flocculation will improve the removal efficiency significantly also for disc filters. Moreover, the measured removal efficiencies were affected by some of the larger particles being broken down into smaller in the disc filters. Creating more stable particles with polymers should both increase the removal efficiency and increase the reliability of the analysis method, especially of *Norovirus* as fewer viruses should be released if fewer particles break. The results from the future scenarios could be implemented on future measurements of removal efficiency for disc filters with coagulation/flocculation to see how that removal efficiency could improve the risk level.

The analysis results of the triplicate samples of indicator bacteria had very high standard deviations, which were transferred to the removal efficiency results. This shows that the sampling and analyses have been connected to high uncertainty, which in turn have contributed to high uncertainty of the level of removal efficiency. The removal efficiency also varied substantially between the different sampling situations. Similar removal efficiencies would be to expect where samples have been analysed for the same microorganism at the same sampling location. Therefore, this confirms the high uncertainty of the results.

Moreover, the removal efficiencies of the composite sample for *E. coli* and the momentary grab sample for total coliforms were negative also with regard to the standard deviation. This is remarkable as that means that the microorganisms should have multiplied within the filter or that a release of particle bound microorganisms during filtration process has occurred. Such results have not been shown in other studies so it is a very unlikely situation. It is more likely that these samples have been subjected to other uncertainties in except for the uncertainties connected to the analysis. Other uncertainties could be improper handling during the sampling, possible growth onto the wall of the sample bottle or that the microorganisms flocculate and therefore cannot be differentiated in the analysis. Another possible reason could be that release of organisms from particles takes place within the turbulent disc filter, in the same way as suspected for *Norovirus*.

The lack of results due to analysis mistakes at laboratory together with the high uncertainty of the results make it difficult to draw any conclusions regarding the removal efficiency of indicator organisms in the different water qualities. However, it could be said that the standard deviation for the disc filters feed from PD is higher than for the filters feed from SS. An explanation for this could be that the water from PD contains fewer but larger particles which could have caused problems with distributing the particles evenly between the triplicate samples and also to homogenise the sample.

Generally, it can be said that the influent to the disc filter facility from the PD consistently contains obviously lower concentrations of all three indicator organisms

than in the influent from SS. A possible explanation for this is that the water entering from the PD treatment has gone through more treatment steps than the water from SS. Compared to previous measurements of microorganisms at Rya WWTP (Åström & Pettersson, 2007; Wilén *et al*., 2012) the concentrations in the influent lie in the same size range. This only applies for the influent from SS since the earlier measurements were made before installation of the post denitrification treatment step. A deviation from this statement is the values of enterococci which seem to be lower at the time of sampling compared to the concentrations presented by Åström & Pettersson (2007). This is though probably due to that the sampling period varies, sampling by Åström & Pettersson (2007) were performed in October.

The first sampling procedure included both momentary grab sampling and composite sampling during 24 h. The momentary sampling shows higher removal efficiencies than the composite samples. The bottles in the composite samplers at the inlet were slightly tilted during the sampling which resulted in smaller amount of water in the bottles during some hours of the sampling. If the concentration of microorganisms were higher during the time when less water was collected at the inlet, this would result in lower removal efficiency than in reality. This could consequently be the reason for the difference between the removal efficiencies.

5.3 Choice of risk assessment method

The risk assessment comprised two different parts; the calculation of the pathogen concentration at the raw water intake from wastewater discharges and the quantification of the reduction in risk for infection among drinking water consumers. The outcome from the risk assessment is characterized by a number of uncertainties due to the choices and approaches that was set up during the planning phase of the assessment as well as uncertainties that remain from the sampling campaign, discussed in Section 5.2.

Several sources of uncertainties can be distinguished from the calculation of the concentration of pathogens at the raw water intake. First, the concentrations at the intake were based on the concentrations in the effluent from the WWTPs. Since information of microbiological data for the wastewater effluent for the WWTPs in question has been sparse it was necessary to assume that effluent data was the same for all WWTPs along Göta älv. Moreover, this effluent data was based on only a few available measurements. This is a major source of uncertainty as the effluent concentrations are bound to differ to some extent despite the close geographical distance and the similar habits that it brings. Second, the total annual outflows of the WWTPs were given but the variation of the outflows of the WWTPs was uncertain. The minimum and maximum outflows from the WWTPs were assumed to be ±15 % of the average. A standard deviation of only 15 % was chosen since the annual effluent flow during 2011 was not very different from the annual effluent flow 2004, which makes it reasonable to assume that the annual outflow is relatively constant. However, the outflow from one second to another might vary more. This was not considered as it is the annual risk reducing potential which is of interest in this report. Third, the flow in Göta älv also varies from year to year. Last, it is important in this context to remember that the uncertainties connected to the removal efficiencies also affect the calculated effluent concentrations after removal by disc filtration. Probability functions were used to manage all these uncertainties when calculating the concentrations at the raw water intake.

Other sources of uncertainties that are important to stress in connection to the transport mechanisms are that no account is taken for inactivation of the pathogens and that total mixing is assumed. The assumption of no inactivation can be seen as a risk increasing action and thereby add to the safety margin. So, in this simplified assessment this assumption is considered to be sound. The assumption of total mixing on the other hand can cause an underestimation of the risk. The same assumption has though been made in many similar studies within Göta älv. As the flow is large and ten kilometres is long compared to the average width and depth of the river it seems reasonable to make this assumption. To get a more realistic flow and mixing pattern more extensive calculations for this can be made for example by CDF modelling, e.g. as been made by Sokolova et al. (2012)

It can also be discussed whether it was correct or not to include the negative removal efficiencies in the average removal efficiencies used in the risk assessment. For some of the sampling situations the calculated removal efficiency seemed to be negative. However, negative removal would only be possible if the microorganisms grow in the filter. As most waterborne microorganisms do not multiply outside a host, this is considered very unlikely. The negative removals were though still included in the average removal efficiencies. The decision to include the negative values as well was based on the observation that the obtained removal efficiencies not only varied between the different sampling situations, but also for similar conditions. This made it difficult to exclude that the negative values were not just a result of the uncertainty of the sampling and analysis and they were included in order not to overestimate the removal.

The presented concentrations are the *most probable* concentrations at the raw water intake. The actual concentrations are likely to vary somewhat over the day and over the year. This means that the concentration at the intake is higher some times and lower other times. Factors influencing this are e.g. that the mean discharge every second and the mean concentrations of pathogen content were used in the calculations. Both these values are seasonal in reality. Additionally, the discharge of *Cryptosporidium* and *Norovirus* will vary by season according to the disease cycle.

It was decided in an early stage that QMRA was an appropriate tool to quantify the reduced risk for the consumers. The Swedish version of this tool is developed for similar conditions as applying for this study and is therefore believed to be suitable for the assessment. It could also have been useful to use another approach for the risk assessment, God Desinfektions Praxis (GDP) which is a tool developed through cooperation between Norsk Vann and Svenskt Vatten. The data used for the MRA is considered to be quite general. Possibly more realistic results could have been generated by studying the processes at Alelyckan in more detail.

5.4 Risk reducing potential for Göteborg

The calculated risk reduction for the drinking water consumers in Göteborg from installing disc filters is true when the high microorganism levels in the river are not detected so that the raw water intake is not closed. It should be seen as the risk reducing potential of only installing disc filters at all upstream WWTPs rather than as the risk for the consumers or as the total risk reducing potential.

The concentration of microorganisms at Lärjeholm would be decreased to some extent if disc filters were installed at all WWTPs discharge to Göta älv. This is a desirable

outcome as potentially the amount of infected persons in Göteborg will be reduced by hundreds. In an extreme situation where there is a low flow in Göta älv, high concentration of pathogens and low treatment at the same time, this decrease could even prevent thousands of infections. However, as already stated, the removal efficiency of microorganisms of disc filters are low compared to other treatment processes. Since the risk reduction is a direct effect of the removal efficiencies of disc filters, other processes would reduce the risk more as well.

For EHEC there was no risk reducing potential at all *E. coli* were removed in the WTP already for the current concentrations. However, it is still important to lower the concentrations in case of reduced capacity at the WTP, as this situation is the prime reason for the need to lower the microorganism concentrations in raw water sources. In addition, the actual concentration at the raw water intake is higher than the concentration out from the WWTPs.

It is also important to remember that a decrease in effluent concentration does not seem to by itself lower the highest peak concentrations below the guideline values, even though normal wastewater discharges is the major source of the baseline concentration in Göta älv. The reason is that the peaks often exceed the guideline values by more than the baseline concentration originating from wastewater discharges. This fact points out the importance of implementing other preventative measures as well to improve the overall microbiological quality of the river. It seems important to lower the peak events, e.g. combined sewage overflow discharge, which often are connected to heavy rain falls. Relevant measures could be to lower overflow volume by decreasing the number of combined wastewater distribution systems, create overflow basins or introduce some microbiological treatment to the overflow volumes.

5.5 General discussion of the risk reducing potential of disc filters

As the removal efficiency of microorganisms of disc filters without coagulation/flocculation appears to be lower than for many other options for tertiary treatment, installing disc filters only for microbiological removal would not be defendable. However, disc filters as a tertiary treatment step at WWTPs seem to remove pathogens to some degree. This means that installation of disc filters has the potential to lower the baseline concentration of pathogens in raw water sources to some extent, which in turn lowers the risk for the drinking water consumers.

Disc filters are also excellent in removing suspended solids and phosphorous and have many benefits, for example being space efficient and easy to install. If disc filters are installed for these reasons, it will bring a beneficial effect on the microbiological concentration in the effluent as well. For WWTPs which require a space efficient tertiary treatment step to improve the effluent quality of suspended solids and phosphorous, the additional positive aspects of the microbial removal could also be seen as a gain. However, if microbiological parameters are important for the choice of tertiary treatment, other processes like slow sand filtration will probably come out better.

5.6 Importance of reducing microbiological risks for raw water sources

The most evident beneficial outcomes reducing the microbiological risks are enhanced human health by reduction of the number of infected persons. This is positive both from an individual perspective and from a national perspective, mainly in terms of rise in personal well-being and fewer days of sick leave. The latter implies that loss of income will be prevented and that production losses will be lowered.

If the government manage to communicate the effort and work spent on these issues the confidence and loyalty could be raised among the consumers. This is contrary to the scenario of a waterborne outbreak. Such situation will most probably have a negative effect of the trust towards the quality of the drinking water and the drinking water producers.

6 Conclusions

The measurement results indicate that disc filters as a tertiary treatment step at WWTPs remove pathogens to some degree. However, the level of the removal efficiency is lower than for some other options for tertiary treatment. Installing disc filters only for microbiological reduction is therefore not defendable.

Though, when disc filters are installed to enhance the removal of suspended solids and phosphorous, it will bring a beneficial effect on the microbiological effluent concentrations as well. For WWTPs which require a space efficient tertiary treatment step to improve the effluent quality, the additional positive aspects of the microbial removal could also be seen as a gain. Still, if enhanced microbiological treatment is the main concern, other treatment processes would be to prefer.

If all WWTPs along Göta älv would install disc filters as a tertiary treatment step the risk of pathogenic impact from drinking water for consumers in Göteborg municipality will decrease. However, a decrease in effluent concentration by disc filtration cannot alone lower the highest peak concentrations to meet the guideline values for raw water. To control these peak concentrations and lower the risk to acceptable levels other measures are necessary.

In general it could be said that large uncertainties of the result call for further studies.

7 Recommendations for further investigations

As the measurement results in this study had large uncertainties and contradicted the theory, the suitability of analysis methods used for measurements over disc filters needs further investigation. It could also be explored if other analysis methods are less dependent of particle content and therefore could be more suitable. If a more suitable analysis method is available it would be interesting to further study variations of the removal efficiency during a cleaning cycle.

Effluent data regarding microorganism discharges from WWTPs are in general very sparse. To lower the uncertainties in assessing risks for raw water sources from WWTPs, the discharges need to be more exhaustively explored. This is also important to increase the knowledge about microbiological parameters in source waters in general.

Since the removal efficiency of disc filters was below desired levels and there is indications that coagulation/flocculation prior to the disc filters will result in higher removal efficiency, it is recommended that this possibility is further studied. Parameters which could be interesting to investigate are how use of different coagulants and flocculants as well as different pore sizes will affect the removal of pathogens. There is also a need to study other options for tertiary treatment to lower microbiological concentrations in wastewater effluent.

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Appendix 1 – Closed intake due to microbial contamination

A compilation of occasions during 2004-2011 when the intake in Lärjeholm had to be kept closed due to microbial detection. Also the total closed time in hours is presented.

Year	Lärjeholm raw water intake closed		
	(h)	Occasions	Due to microbiological detection (%)
2004[a]	2 851	55	85
2005[b]	2 123	49	70
2006[c]	2 780	49	90
2007[d]	2 701	77	80
2008[e]	2 712	51	73
2009[f]	2 231	74	52
2010[g]	1 546	46	77
2011[h]	2 265	70	53
Average	2 401	59	73

[a] Göta älvs vattenvårdsförbund (2005)
[b] Göta älvs vattenvårdsförbund (2006)
[c] Göta älvs vattenvårdsförbund (2007b)
[d] Göta älvs vattenvårdsförbund (2008)
[e] Göta älvs vattenvårdsförbund (2009)
[f] Göta älvs vattenvårdsförbund (2010)
[g] Göta älvs vattenvårdsförbund (2011)
[h] Göta älvs vattenvårdsförbund (2012)

The average number of days when the intake was closed was calculated:

2401 hours/24 hour = 72.5 days

Appendix 2 - Calculation of *Cryptosporidium* and *Norovirus* concentrations in WWTP effluent

To calculate the concentrations of *Cryptosporidium* and *Norovirus* in WWTP effluent it was necessary to assume similar removal efficiencies for *Cryptosporidium* as for *Clostridium Perfringens* and also similar removal efficiencies for *Norovirus* as for Coliphages. The average removal efficiency of *Clostridium Perfringens* at Arvidstorp WWTP is presented below:

Date	IN[a] (cfu/100 ml)	OUT[a] (cfu/100 ml)	Removed (cfu/100 ml)	Removal efficiency $R_{Clostridium\ Perfringens}$ (%)
2011-06-07	120000	3300	116700	0.973
2011-06-28	45000	7100	37900	0.842
2011-07-07	84700	730	83970	0.991
2011-07-19	83000	1700	81300	0.980
2011-08-03	44000	340	43660	0.992
2011-08-15	86000	1500	84500	0.983
2011-08-30	24000	6700	17300	0.721
2011-09-14	34000	12000	22000	0.647
2011-09-28	74000	1000	73000	0.986
2011-10-12	76000	13000	63000	0.829
2011-10-24	90000	4100	85,900	0.954
2011-11-07	77000	1200	75800	0.984
2011-11-21	78000	2200	75800	0.972
2011-12-12	47000	5400	41600	0.885
2011-12-21	71000	2700	68300	0.962
2012-01-04	32000	8400	23600	0.738
2012-01-18	84000	2300	81700	0.973
			Average:	*0.907*

[a] Unpublished measurement from the VISK project.

Concentration of *Cryptosporidium* in Swedish raw wastewater (from Table 2 in Section 2.2.1.1):

$$C_{influent,Cryptosporidium} = 10^{1.3} \text{ numbers/litre}$$

Calculated average concentration of *Cryptosporidium* in WWTP effluent given the assumption of similar removal efficiency for *Cryptosporidium* as for *Clostridium Perfringens*:

$$C_{effluentWWTP,\ Cryptosporidium} = C_{influent,Cryptosporidium} \cdot R_{Clostridium\ Perfringens}$$

$$C_{effluentWWTP,\ Cryptosporidium} = 10^{1.3} \text{ numbers/litre} \cdot 0{,}907 = \mathbf{1.816\ numbers/100\ ml}$$

Average removal efficiency of Coliphages at Arvidstorp WWTP is presented below

Date	IN[a] (cfu/100 ml)	OUT[a] (cfu/100 ml)	Removed (cfu/100 ml)	Removal efficiency $R_{Coliphages}$ (%)
2011-06-07	-	8700	-	-
2011-06-28	1300000	25000	1275000	0.981
2011-07-07	220000	30000	190000	0.864
2011-07-19	-	-	-	-
2011-08-03	27000	11000	16000	0.593
2011-08-15	110000	11000	99000	0.900
2011-08-30	80000	6000	74000	0.925
2011-09-14	33000	15000	18000	0.545
2011-09-28	-	-	-	-
2011-10-12	150000	16000	134000	0.893
2011-10-24	48000	4000	44000	0.917
2011-11-07	490000	3900	486100	0.992
2011-11-21	-	-	-	-
2011-12-12	9000	15000	-6000	-0.667
2011-12-21	150000	16000	134000	0.893
2012-01-04	400 00	1600	38400	0.960
2012-01-18	100000	10000	90000	0.900
			Average:	*0.746*

[a] Unpublished measurements from the VISK project.

Concentration of *Norovirus* in Swedish raw wastewater (from Table 2 in Section 2.2.1.1):

$$C_{influent,\ Norovirus} = 10^{3.3} \text{ numbers/litre}$$

Average concentration of *Norovirus* in effluent given the assumption of similar removal efficiency for *Norovirus* as for Coliphages:

$$C_{effluentWWTP,\ Norovirus} = C_{influent,\ Norovirus} \cdot R_{Coliphages}$$

$$C_{effluentWWTP,\ Norovirus} = 10^{3.3} \text{ numbers/litre} \cdot 0.746 = \mathbf{149.645\ numbers/100\ ml}$$

Appendix 3 – Particle distribution

Results from analysis of particle size distribution. Samples were taken at the first sampling occasion, 8 March, 2012, from both influent and effluent water from two disc filters units, one with feed from SS effluent and one with feed from PD effluent.

The samples were taken as momentary single samples direct in an open disc filter unit.

Particle size interval (µm) Average	Particle diameter (µm)	Disc filter feed from SS		
		Influent (number)	Effluent (number)	Removal (%)
1-2	1.5	16063	25471	-58.6
2-5	3.5	2547	2118	16.8
5-10	7.5	225	225	-
10-15	12.5	46	23	50.0
15-20	17.5	18	4	77.8
20-30	25	-	4	-
30-50	40	4	5	-25.0
>50	50	114	8	93.0

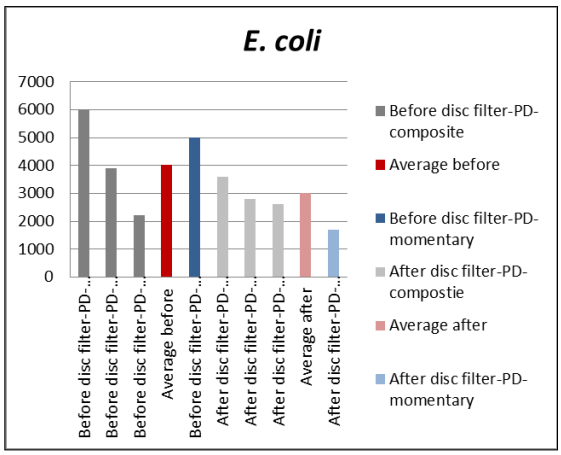
Particle size interval (µm) Average	Particle diameter (µm)	Disc filter feed from PD		
		Influent (number)	Effluent (number)	Removal (%)
1-2	1.5	9721	14708	-51.3
2-5	3.5	1102	1494	-35.6
5-10	7.5	170	159	6.5
10-15	12.5	76	24	68.4
15-20	17.5	37	4	89.2
20-30	25	-	3	-
30-50	40	-	5	-
>50	50	338	8	97.6

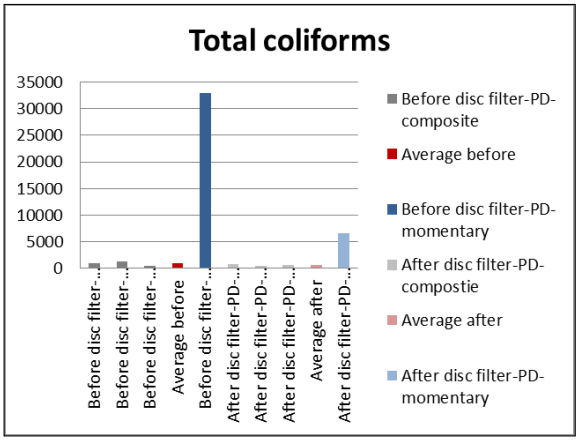
Appendix 4 - Concentrations from sampling 6-8 March, 2012

The concentrations of indicator organisms and pathogens in samples taken from one of the disc filter units receiving water from **PD** are presented below. The samples were collected during the first sampling occasion, 6-7 March 2012, as composite sampling during 24 h (one sub-sample every hour). These samples were analysed in triplicates. Additional momentary grab samples collected 7 March 2012 were analysed as singles.

Sample	Total Coliforms (numbers/ 100 ml)	*E. coli* (numbers/ 100 ml)	Enterococci (cfu/100 ml)	*Norovirus* (numbers/ 100 ml)	
				GI	GII
Inlet, composite 24 h	980	6000	2000	6408	23836
Inlet, composite 24 h	1300	3900	-	10066	40310
Inlet, composite 24 h	520	2200	-	13459	52575
Average, inlet	*933*	*4033*	-	*9977*	*38907*
Outlet, composite 24 h	750	3600	-	13912	83861
Outlet, composite 24 h	410	2800	-	11958	73158
Outlet, composite 24 h	630	2600	-	8375	49246
Average, outlet	*597*	*3000*	-	*11415*	*68755*
Inlet, momentary grab sample	1,90E+04	2900	1800	-	-
Outlet, momentary grab sample	16000	3900	2000	-	-

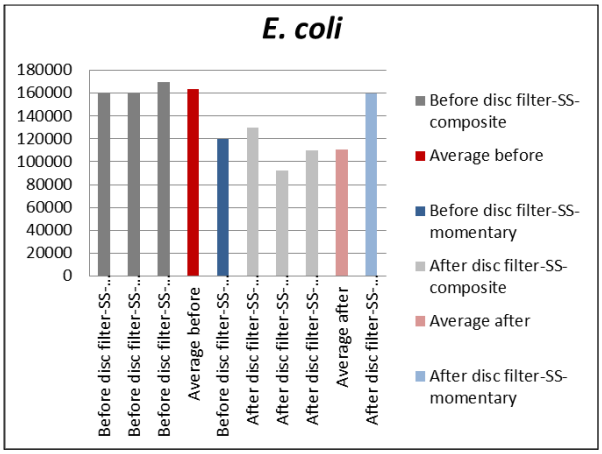
According to Lackarebäck the analysis of Enterococci showed values far under the normal concentrations in wastewater from Rya WWTP. Possibly it could have depended upon an error in the dilution during the preparation of the sample.

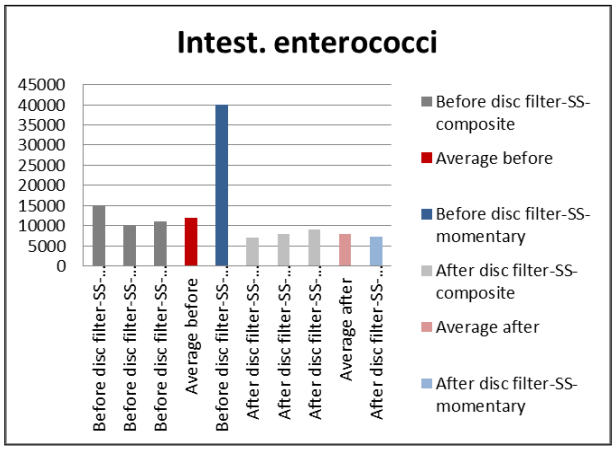


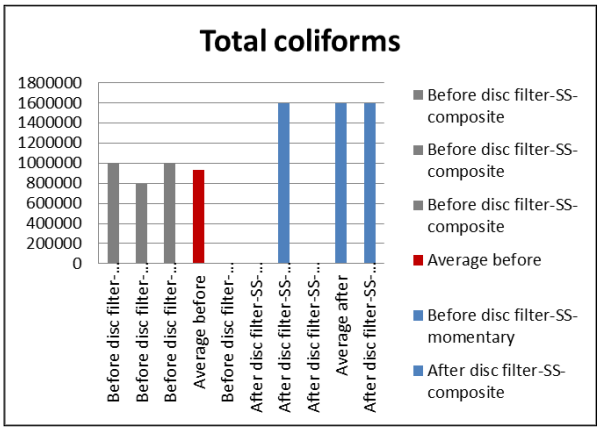


The concentrations of indicator organisms and pathogens in samples taken from one of the disc filter units receiving water from **SS** are presented below. The samples were collected during the first sampling occasion, 7-8 March 2012, as composite sampling during 24 h (one sub-sample every hour). These samples were analysed in triplicates. Additional momentary grab samples collected 8 March 2012 were analysed as singles.

Sample	*E. coli* (numbers/ 100 ml)	Enterococci (cfu/100 ml)	Total Coliforms (numbers/ 100 ml)	*Norovirus* (numbers/ 100 ml)	
				GI	GII
Inlet, composite 24 h	160000	15000	1,00E+06	8767	56495
Inlet, composite 24 h	1,60E+05	10000	7,90E+05	10504	79182
Inlet, composite 24 h	1,63E+05	12000	930000	6540	51498
Average, inlet	*1,70E+05*	*11000*	*1,00E+06*	*8604*	*62392*
Outlet, composite 24 h	130000	7000	-	12104	72184
Outlet, composite 24 h	92000	8000	1,60E+06	15841	71710
Outlet, composite 24 h	110000	9100	-	17738	56554
Average, outlet	*110667*	*8033*	*1600000*	*15228*	*66816*
Inlet, momentary grab sample	1,20E+05	4,00E+04	-	-	-
Outlet, momentary grab sample	1,60E+05	7300	1,60E+06	-	-

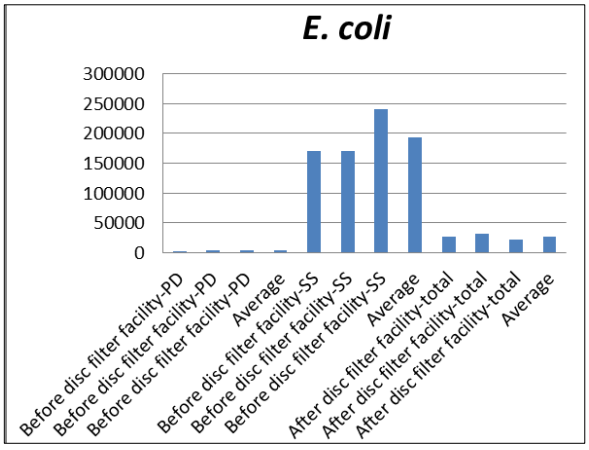


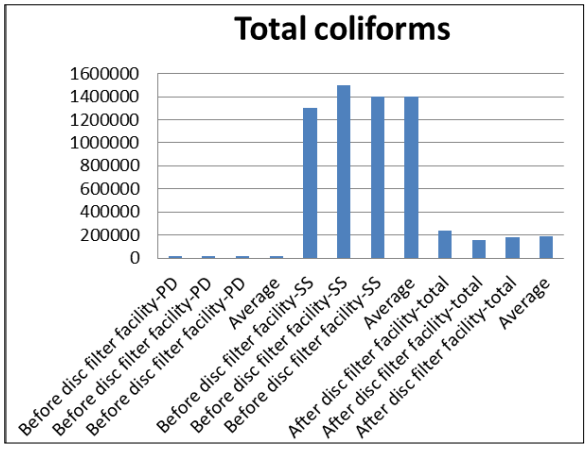


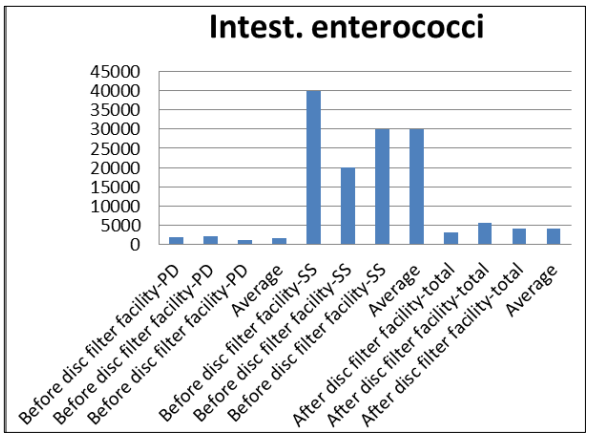


The concentrations of indicator organisms in samples collected over the entire disc filter facility (sampling locations A, B and C) are presented below. The samples were collected during the first sampling occasion, 8 March 2012, as composite sampling during one hour (one sub-sample every fifteen minute). These samples were analysed in triplicates.

Sample	*E. coli* (numbers/100 ml)	Enterococci (cfu/100 ml)	Total Coliforms (numbers/100 ml)
Inlet, from PD	2900	1800	1,90E+04
Inlet, from PD	3900	2000	16000
Inlet, from PD	3400	1000	15000
Average, from PD	*3400*	*1600*	*16667*
Inlet, from SS	1,70E+05	4,00E+04	1,30E+06
Inlet, from SS	1,70E+05	20000	1,50E+06
Inlet, from SS	2,40E+05	30000	1,40E+06
Average, from SS	*1,93E+05*	*30000*	*1400000*
Total outlet	2,60E+04	3000	2,40E+05
Total outlet	3,10E+04	5500	1,60E+05
Total outlet	2,20E+04	4000	1,80E+05
Average, outlet	*2,63E+04*	*4166*	*193333*







Appendix 5 - Concentrations from sampling 28-30 May, 2012

The concentrations of indicator organisms and pathogens in samples taken from one of the disc filter units receiving water from PD are presented below. The samples were collected during the second sampling occasion, 28-29 May, 2012, as composite sampling during 24 h (one sub-sample every hour).

Sample	*E. coli* (numbers/100ml)	*Clostridium Perfringens* (cfu/100ml)	Somatic coliphages (pfu/100ml)	*Norovirus* (numbers/ 100ml)	
				GI	GII
Inlet	1400	3800	9000	12912	4179
Outlet	500	770	15000	43175	13134

The concentrations of indicator organisms and pathogens in samples taken from one of the disc filter units receiving water from SS are presented below. The samples were collected during the second sampling occasion, 29-30 May, 2012, as composite sampling during 24 h (one sub-sample every hour).

Sample	*E. coli* (numbers/100ml)	*Clostridium Perfringens* (cfu/100ml)	Somatic coliphages (pfu/100ml)	*Norovirus* (numbers/ 100ml)	
				GI	GII
Inlet	14000	2300	14000	47277	10886
Outlet	15000	1900	28000	70304	41210

Appendix 6 - Annual probability of infection and number of infected persons

The output values from the MRA for all scenarios (0-5) are presented below. The annual probability of infection is presented for the 0.05-, 0.25-, 0.50-, 0.75- and 0.95-percentile. Number of infected persons in Göteborg municipality (caused by wastewater discharges) is presented both for the average case (0.50) and the worst case (0.95). *Inhabitants in Göteborg municipality: 521 587*

Scenario 0	Annual probability of infection		
	Bacteria	*Norovirus*	*Cryptosporidium*
0.05	0.00E+00	2.18E-05	1.61E-04
0.25	0.00E+00	1.26E-04	9.98E-04
0.50	0.00E+00	4.83E-04	3.91E-03
0.75	0.00E+00	1.82E-03	1.49E-02
0.95	0.00E+00	8.43E-03	7.36E-02
Number of infected persons in Göteborg Average (0.50)	0	252	2041
Number of infected persons in Göteborg Worst case (0.95)	0	4395	38373

Scenario 1	Annual probability of infection		
	Bacteria	*Norovirus*	*Cryptosporidium*
0.05	0.00E+00		8.26E-05
0.25	0.00E+00		5.62E-04
0.50	0.00E+00		2.31E-03
0.75	0.00E+00		8.96E-03
0.95	0.00E+00		4.88E-02
Number of infected persons in Göteborg Average (0.50)	0	0	1205
Number of infected persons in Göteborg Worst case (0.95)	0	0	25435

Scenario 2	Annual probability of infection		
	Bacteria	*Norovirus*	*Cryptosporidium*
0.05	0.00E+00	6.40E-06	4.41E-05
0.25	0.00E+00	3.73E-05	2.80E-04
0.50	0.00E+00	1.43E-04	1.11E-03
0.75	0.00E+00	5.46E-04	4.24E-03
0.95	0.00E+00	2.58E-03	2.11E-02
Number of infected persons in Göteborg Average (0.50)	0	75	579
Number of infected persons in Göteborg Worst case (0.95)	0	1344	10995

Scenario 3	Annual probability of infection		
	Bacteria	*Norovirus*	*Cryptosporidium*
0.05	0.00E+00	4.20E-06	3.36E-05
0.25	0.00E+00	2.47E-05	2.07E-04
0.50	0.00E+00	9.63E-05	8.28E-04
0.75	0.00E+00	3.58E-04	3.09E-03
0.95	0.00E+00	1.69E-03	1.58E-02
Number of infected persons in Göteborg Average (0.50)	0	50	432
Number of infected persons in Göteborg Worst case (0.95)	0	883	8231

Scenario 4	Annual probability of infection		
	Bacteria	*Norovirus*	*Cryptosporidium*
0.05	0.00E+00	2.15E-06	1.68E-05
0.25	0.00E+00	1.25E-05	1.04E-04
0.50	0.00E+00	4.78E-05	4.15E-04
0.75	0.00E+00	1.81E-04	1.56E-03
0.95	0.00E+00	8.34E-04	7.90E-03
Number of infected persons in Göteborg Average (0.50)	0	25	216
Number of infected persons in Göteborg Worst case (0.95)	0	435	4121

Scenario 5	Annual probability of infection		
	Bacteria	*Norovirus*	*Cryptosporidium*
0.05	0.00E+00	2.16E-07	1.71E-06
0.25	0.00E+00	1.26E-06	1.05E-05
0.50	0.00E+00	4.81E-06	4.11E-05
0.75	0.00E+00	1.84E-05	1.55E-04
0.95	0.00E+00	8.53E-05	7.86E-04
Number of infected persons in Göteborg Average (0.50)	0	3	21
Number of infected persons in Göteborg Worst case (0.95)	0	44	410