CHALMERS

# Microbiological Risk Analysis of Kungälv Drinking Water Treatment Plant

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


FLORENCE ATUBO, MINA MAFINEJADASL

Department of Civil and Environmental Engineering

*Division of Water Environment Technology*

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden, 2012



Report No. 2012:142

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Chalmers Tekniska Högskola 2012:142

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Cover:

From left: View of Göta älv (Göta älv, u.d.), upper picture to the right: Combined Sewer Overflows (Daily Interesting Facts, 2012), lower picture: Adenovirus (ISIS INNOVATION, u.d.)



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## Acknowledgement

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Thank you all very much!!



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## Abstract

Human activities are changing the world's climate by increasing energy-trapping gases responsible for the "green-house" effect. The world's average temperature has increased by approximately 0.6$^{o}$C and approximately two thirds of that warming has occurred since 1975. Further warming is forecast together with changes in precipitation and climatic variability in the coming century. Temperatures are expected to increase more in Sweden and Scandinavia than the global mean. Changes in temperature and runoff will have an effect on quality of raw water sources for drinking water. Humus levels, algal bloom and microbial contamination will increase in raw water sources as a result and present-day drinking water treatment processes will be inadequate in achieving the recommended health targets, causing waterborne disease outbreaks. In order to prepare for the predicted precipitation increase due to climate change and its effects on raw water sources, the municipality of Kungälv, has decided to design a new treatment plant carried out by Norconsult AB.

The main aim of the study is to assess whether the proposed drinking water treatment plant will be effective in removing pathogens to a level that fulfils the USEPA guideline value. The study investigated the health risks that the consumers in Kungälv are exposed to today and in the future by studying the operation and reliability of the processes in the proposed treatment plant, and their removal efficiency of pathogens. The health risks were calculated through literature reviews and by application of the Quantitative Microbiological Risk Assessment tool developed by the Swedish Water and Wastewater Association. Risk analyses were conducted in three scenarios: for present conditions, future up to 2060 and the case of a waterborne disease outbreak upstream the raw water intake for Kungälv.

The result showed that the population of Kungälv connected to the current drinking water treatment plant seem to be very vulnerable to waterborne disease infection since the model indicates no effective pathogen removal. The annual risks of infection for all pathogens except *Salmonella* were above the USEPA guideline values. This demonstrates the importance of the proposed treatment plant, which will provide better pathogen removal and inactivation barriers. However, the study also shows that while being effective in removal of other pathogens, the proposed plant is not capable of fully removing Adenoviruses without the using chlorination. To be able to achieve safe drinking water with the proposed DWTP, chlorination is recommended to be used all year round to reduce the infection risk today as well as in the future (2060). The study also recommends that sources of contamination like wastewater from combined system overflows be directed to wastewater treatment systems like treatment ponds in order to reduce the pathogen loads to the raw water.

**Key words**: Pathogen concentration, QMRA, Adenovirus, Climate change, Drinking Water Treatment Plant, Kungälv, Göta älv, Risk of infection, Risk analysis



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Mikrobiologisk Riskanalys av Kungälvs dricksvatten reningsverk

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## Sammanfattning

Mänskliga aktiviteter förändrar jordens klimat genom ökade utsläpp av olika gaser som bidrar till växthuseffekten. Världens medeltemperatur har ökat med cirka 0,6$^{o}$C och ungefär två tredjedelar av uppvärmningen har skett sedan 1975. Under det kommande århundradet förväntas en ytterligare uppvärmning tillsammans med förändringar i nederbörd och klimatvariationer. Temperaturen väntas i medeltal öka mer i Sverige och Skandinavien än t globalt. Förändringar i temperatur och markavrinning kommer att ha effekt på kvaliteten i dricksvattentäkter. Humushalter, algblomning och mikrobiella föroreningar förväntas öka i råvattenkällor som ett resultat och dagens behandlingsprocesser för att bereda dricksvatten kommer att vara otillräcklig för att uppnå de rekommenderade hälsokraven vilket upphov till vattenburna sjukdomsutbrott. Kungälvs kommun har beslutat med Norconsult som projectör att bygga ett nytt dricksvattenreningsverk på grund av förutspådda klikatförändringama och dess effekter på råvattenttäkter.

Syftet med studien var att bedöma om det föreslagna vattenverket kommer att vara effektivt tillräckligt för att avlägsna patogener till den nivå som uppfyller den amerikanska miljövårdsmyndighetens (USEPA) riktvärde. I studien undersöktes de hälsorisker som konsumenterna i Kungälv utsätts för idag och i framtiden genom att studera funktionen och tillförlitligheten av de processerna i det föreslagna vattenverket och reningseffektivitet av patogener. Hälsorisker beräknades med hjälp av kvantitativ mikrobiell riskanalys (QMRA) verktyg som utvecklats av Svenskt Vatten. Riskanalyser utfördes utifrån scenarier för nuvarande och en framtida situation samt för ett vattenburet sjukdomsutbrott uppströms råvattenintaget vid Kungälvs vattenverk.
Resultatet visade att det finns risker för befolkningen i Kungälv som är ansluten till detbefintliga vattenverket att de drabbas av infektion eftersom det nuvarande vattenverket inte är tillräckligt effektivt att avlägsna patogener. De årliga riskerna för infektion för alla patogener utöver *salmonella* låg över den amerikanska miljövårdsmyndighetens (USEPA) riktvärden för det nuvarande systemet. Det är därför viktigt att uppgradera det nuvarande vattenverket med det föreslagna processerna som har bättre patogeninaktivering/reducering. Men studien visar också att vattenverket inte avskilja/inaktivera Adenovirus tillräckligt utan att använd klorering. För att kunna leverera ett rent dricksvatten med det föreslagna vattenverket, rekommenderas användning av klorering året runt för att minska infektionsrisken redan idag och i framtiden (2060). Studien rekommenderar också att åtgärder vidtas föratt minska effekterna från föroreningskällor såsom bräddning av avloppsvatten med utsläpp patogena ämnena till råvattentäkten.

**Nyckelord**: Patogen halter, QMRA, Adenovirus, Klimat förändring, Dricksvatten reningsverk, Kungälv, Göta älv, Infektionsrisk, Riskanalys



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## Acronyms

AWWA - American Water Works Association

CSOs -Combined Sewer Overflows

DALY- Disability Adjusted Life Years

DNA - Deoxyribonucleic acid

DWTP - Drinking Water Treatment Plant

EHEC - *Enterohaemorrhagic Escherischia coli*

IPCC- Intergovernmental Panel on Climate Change

NFA-National Food Administration

PAC - Polyaluminum Chloride

QMRA- Quantitative Microbial Risk Assessment

RNA - Ribonucleic acid

SCCV - Swedish Commission on Climate and Vulnerability

SDWF - Safe Drinking Water Foundation

SVU- Svensk Vatten Utveckling

SWWA - The Swedish Water and Wastewater Association

UN - United Nations

USEPA -United States Environmental Protection Agency

UV – Ultra Violet

WWTP - Waste Water Treatment Plant



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# 1 Introduction

The world's climate system is fundamental to the stability of ecosystems and human societies that depend on it. Today however, human activities are changing the world's climate by increasing energy-trapping gases responsible for the "green-house" effect. These gases comprise mainly carbon dioxide (from fossil fuel combustion and forest burning), methane (from agriculture, animal husbandry and oil extraction), nitrous oxides and manmade halocarbons (WHO, 2003).

The UN's Intergovernmental Panel on Climate Change (IPCC) in its third report stated that *"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."* During the twentieth century, the world's average temperature has increased by approximately 0.6 $^{o}$C and approximately two thirds of that warming has occurred since 1975. Further warming is forecast together with climatic variability including precipitation in the coming century, and these forecasts are based on sophisticated global climate models (WHO, 2003)

General mean annual precipitation is projected to increase in northern Europe and decrease in the south. The changes in precipitation are also predicted to vary from season to season and across regions according to changes in large-scale circulation and water vapour loading. Annual runoff is projected to increase in northern Europe by approximately 5-15% up to the 2020's and by 9-22% up to the 2070's. These precipitation changes will have a range of impacts on water resources especially risks that arise from floods (IPPC, 2008).

Sweden is not exempt from these changes. Temperatures are expected to rise more in Sweden and Scandinavia than the global mean. There has been significant warming in Sweden since the late 1980s and the past 15-20 years have been distinctly warm where for example the average temperature in winter has been 1 $^{o}$C higher than a hundred years ago. The difference in winter temperature between 1961-1990 and 1991-2005 is around 2 $^{o}$C (SCCV, 2007).

From hydrological calculations, annual runoff will increase over greater parts of Sweden particularly in Norrland and in western Götaland. In parts of the country where precipitation is expected to increase, floods are likely to happen and this may affect the water supply. These increases in temperature and runoff will have impacts on both inland and sea waters. At the moment Sweden has access to large quantities of good quality water but these changes in temperature and runoff will have an effect on the quality of raw water sources for drinking water. Humus levels, algal bloom and microbial contamination will increase as a result and present-day treatment processes will be inadequate (SCCV, 2007). The increased risk of floods and landslides may also mean that pollution from contaminated soil and old landfills can be spread (Regeringskansliet, 2009).

Half of Sweden's water supply comes from surface water (lakes, rivers and streams) and the other half from groundwater which is mainly infiltrated surface water. Because of the comparatively good quality of raw water from these sources, the treatment techniques in Sweden are relatively simple. Treatment plants that use groundwater as raw water often use simpler techniques than surface water treatment plants. The common processes as microbial barriers in a surface water treatment plant are chemical precipitation including filtration and chlorination as a disinfection process (SCCV, 2007).



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There is need for adaptation to the predicted climate change and the water management challenges that come with it. For Sweden, this is particularly concerning the risk of flooding. Strategies for reducing vulnerability to climate change must be coupled with efforts to cut climate emissions. At national levels, construction of reservoirs, dykes and flood plains are the main measures to protect against flooding (IPPC, 2008). Complementary strategies for water treatment plants would require design of efficient water treatment technologies to cope with the expected change in water quality.

Good quality water supply is a prerequisite for modern life and local authorities are responsible for water and sewage in the urban areas. Sweden has approximately 2000 publicly owned water works serving a population of about 7.7 million (82% of the current population), 10% of which use surface water as raw water sources. The surface water works serve 51% of this population; ground water serves 23% and artificial groundwater (infiltrated surface water) plants serve 26%. In Sweden, although quality of drinking water is the responsibility of the Ministry of Agriculture with the National Food Administration as the central supervising agency, water supply and sanitation management is the duty of the local government or municipality (SWWA, 2000). This implies that the preparations for adapting to climate change are the responsibility of the municipality where the water supply plants are located.

The Göta älv which is the source for Kungälv is considered of poor quality by Swedish standards. The municipality of Kungälv currently supplies water to consumers taken through a very simple drinking water treatment system (see chapter 2) but in order to prepare for the predicted increase in precipitation due to climate change, a new treatment plant has been proposed.

***Study area***

Kungälv municipality covers an area of 364 square kilometres in Västra Götaland, Sweden and is bordered by Gothenburg, Stenungsund, Tjörn and Ale municipalities. The current population of Kungälv is 41 473 inhabitants and is predicted to increase to 64 600 by year 2035 (Kungälvs Kommun, 2011) and probably 90 600 inhabitants by 2060 if the population prediction factors remain the same.

Drinking water in Kungälv has to meet the quality requirements of the National Food Administration. To ensure that this quality is achieved, the municipality has three water treatment plants: Dösebacka, Lysegården and Marstrand. These plants supply water to about 25 000 people with an approximate consumption of 0.2 $m^3$/p*day (200 l/p*day). The raw water source for the treatment plants is River Göta Älv although they have different treatment methods. Dösebacka and Lysegården plants treat water through artificial recharger infiltration and thereafter only pH-adjustment is performed while Marstrand is a surface water treatment plant with chemical treatment and sand filtration (Kungälvs Kommun, 2011).

The raw water in Kungälv has today seemed to be of sufficient quality to require only basic treatment but in preparation for future climate change and its impacts, a new treatment plant has been proposed for Dösebacka. The proposed plant will supply water to Kungälv, Ale, Stenungsund and Tjörn municipalities (Figure 1).



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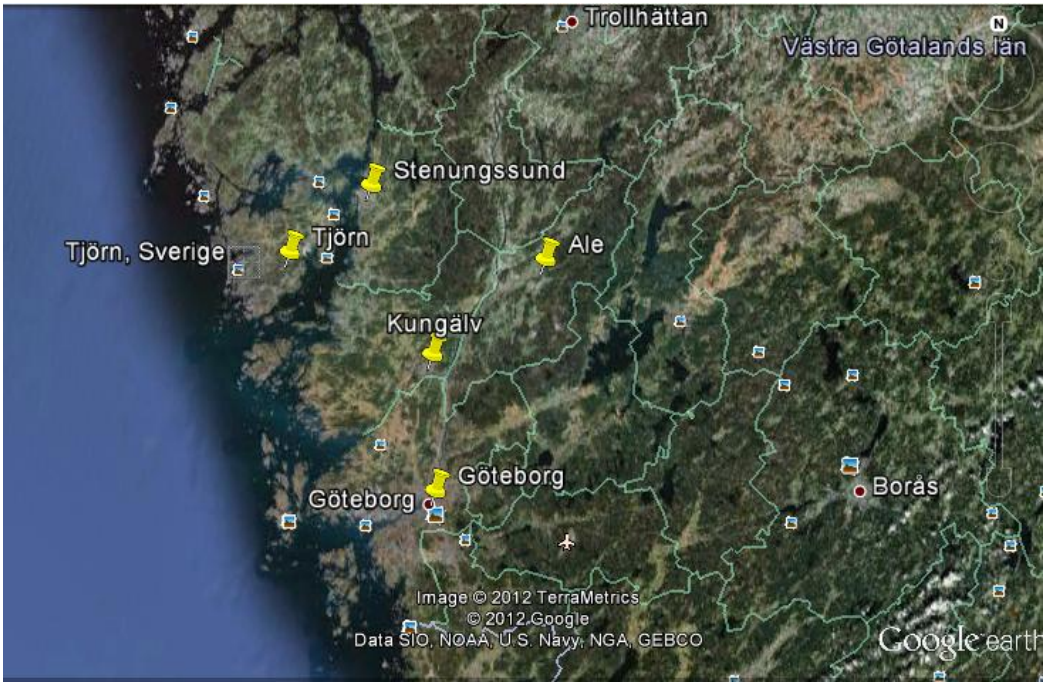


**Figure 1. Municipalities of Kungälv, Ale, Stenungsund and Tjörn (Google earth, u.d.)**

## 1.1 Problem Statement

Climate change scenarios do show an increase in temperature and precipitation, which results in increased water runoff into surface and underground water sources. Greater runoff leads to the surface water increase, hence increasing the humic acid levels, algal bloom and microbial contamination that negatively affect the water quality. Higher levels of precipitation are likely to increase agricultural runoff, flows of urban stormwater and sanitary sewage to drainage basins (Figure 2). The River Göta Älv which is a source of raw water for five drinking water treatment plants has been identified as an area of concern with risks of floods, landslides and dam failures (Karlsson, 2009). Concentrations of indicator bacteria *Escherichia coli* have been detected in Göta Älv at levels as high as 2800 CFU/100ml in 2006, which is more than five times the Swedish guideline value of 500 CFU/100ml (Åström, 2007). The presence of *E.coli* demonstrates the presence of faecal pollution and possible pathogens. Consumption of poor water quality may result in serious illness due to pathogens like bacteria, viruses and protozoa (Figueras & Borrego, 2010).

The Swedish National Food Administration states that between 1 and 13 waterborne outbreaks have been reported annually in Sweden with infection from various pathogens ranging from 100 to over 10 000 individuals. The annual infection risk from waterborne outbreaks has been estimated to be 1 in 10 000 in Sweden (Lindberg & Lindqvist, 2005). A study performed by Svensk Vatten Utveckling (SVU) for Göta Älv shows that the microbial load in the river water is significantly affected by the discharges of wastewater such as combined sewer overflows –'CSOs', emergency discharges and wastewater treatment plant effluents (Åström & Pettersson, 2007).

In order to prevent waterborne outbreaks, drinking water must be effectively treated. The current drinking water treatment system used in Kungälv whose treatment barriers include sedimentation and infiltration may not efficiently remove pathogens if the water quality deteriorates further. This impelled the design of a new drinking water treatment plant (DWTP) to meet the challenge of varying water



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quality both at present and in the future. The proposed plant should have efficient treatment processes to ensure that drinking water quality is safe for the consumers.

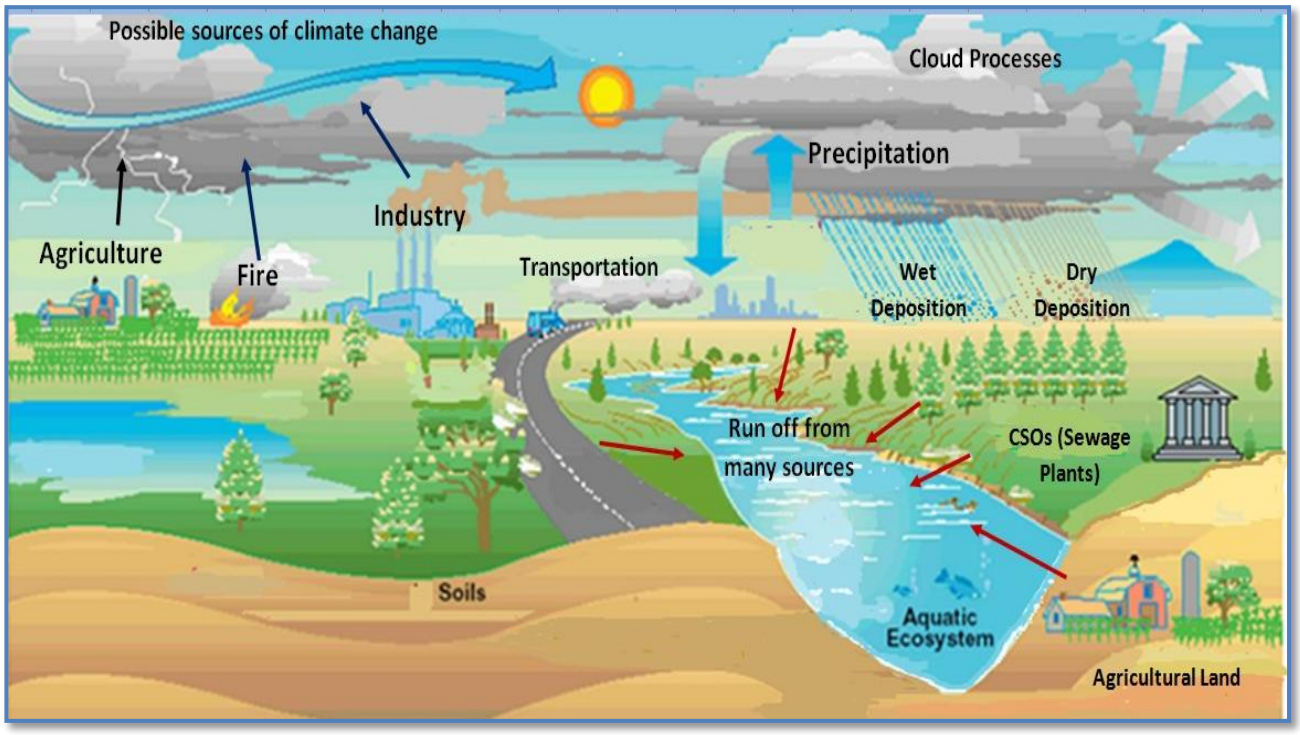


**Figure 2. Conceptual model of pathogen flow into the surface water due to increased precipitation – adapted from a blog of school of Peniche (Anon., 2008)**

## 1.2 Aim and objectives

The main aim of the study is to assess whether the proposed drinking water treatment plant designed by Norconsult is effective in removing pathogens to a level that fulfils the USEPA guideline value. Areas of improvement in the proposed DWTP will also be recommended. The study investigates the health risks that the consumers in Kungälv are exposed to today and in the future by studying the operation and reliability of the processes in the proposed treatment plant, and their removal efficiency of pathogens.

Scenarios with pathogens discharged into the raw water source for the proposed water treatment plant are used to determine the safety of the treatment processes. These scenarios include functioning of the system for the conditions of today, pathogen loading in the future (up to 2060) and determine the loading that would cause waterborne disease outbreaks.

The proposed treatment plant is tested for its capability (removal efficiency) in removing pathogens in order to fulfil prescribed health targets (Appendix 1). It is recommended that the plant should achieve a health based target in which no more than one person in a population of 10 000 becomes infected annually ($1 \times 10^{-4}$) (Signor & Ashbolt, 2009).

## 1.3 Scope

This study is conducted for the Kungälv municipality and is a microbiological risk analysis performed on the current and a new proposed treatment plants for Kungälv, using the River Göta Älv as the raw water source. Traditionally, faecal pollution indicator microorganisms have been used to estimate the



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presence of pathogens in drinking water. However, cases have been found where the pathogens have existed in the absence of indicator organisms (Figueras & Borrego, 2010). This governed our study of the treatment system to focus on the pathogens normally found in Sweden (River Göta Älv) instead of using indicator organisms only. The pathogens studied are in three categories: viruses (Adenovirus, Norovirus, and Rotavirus), bacteria (*Campylobacter*, *Salmonella*, *Enterohaemorrhagic Escherischia coli* - EHEC) and protozoa (*Cryptosporidium, Giardia*).

The investigative study was carried out using the Swedish Quantitative Microbiological Risk Assessment (QMRA) tool developed by the Swedish Water & Wastewater Association that determines health risks to drinking water consumers (Svensk Vatten Utveckling, 2012). The newly proposed drinking water treatment system has several processes (section 2.2), which have been evaluated using the QMRA model and include: direct filtration (DynaSand filters), infiltration basins, rapid sand filtration, UV-disinfection and chlorination during emergency situations.



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## 2. Drinking Water Treatment

This study focused on the pathogenic microorganisms in raw water and the treatment processes that may be used to remove or inactivate them in order to meet water quality guidelines and targets. Surface water in Sweden naturally contains more humus than groundwater. Therefore it contains more organic particles and, microorganisms and is likely to exhibit variations in quality. Consequently more efficient and robust microbial barriers are needed for drinking water treatment plants (DWTP) with surface water as the raw water source (Lindberg & Lindqvist, 2005). The efficiency of a microbial barrier depends on two factors: removal and inactivation and in drinking water production it is preferable that both factors are considered (Figure 3). The reduction achieved by the barrier is expressed as a logarithmic equation (Engblom & Lundh, 2006). $Log_{10}$- reduction shows the relative number of microbes eliminated by a treatment processes. One $log_{10}$ reduction means that the pathogens are reduced 10 times (pathogens decrease by 90%) (Healthy Facilities Institute, 2012).

$$Logreduction = \left(-Log_{10}\left(\frac{C}{C_0}\right)\right) \quad (1)$$

$C = Number\ of\ microorgansims\ after\ passing\ through\ a\ barrier$

$C_0 = Number\ of\ microorgansims\ before\ passing\ through\ \ a\ barrier$

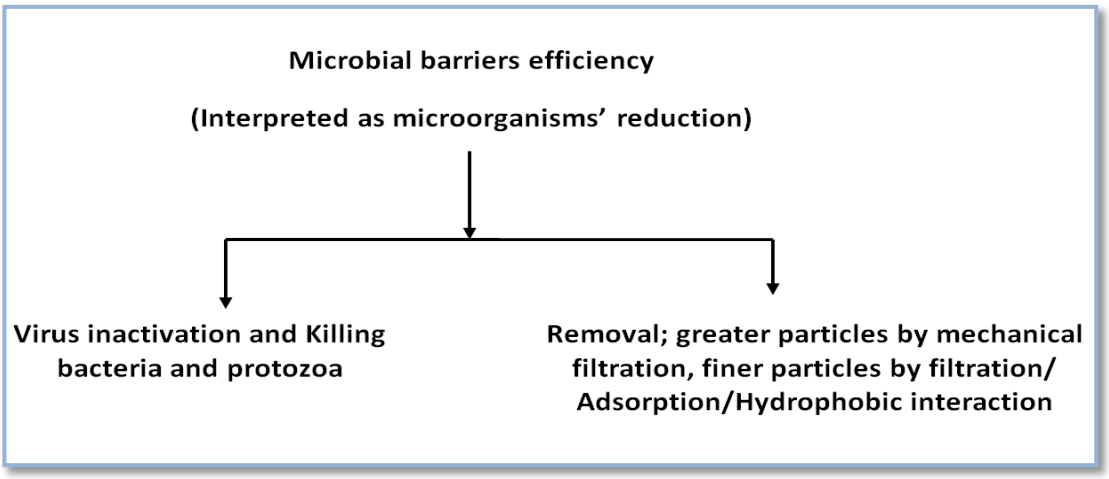


**Figure 3. Microbial barriers efficiency (Engblom & Lundh, 2006)**

A treatment train involving chemical precipitation and filtration (slow sand filtration and /or rapid sand filtration where rapid sand filtration is much more common than slow sand filtration) is traditionally performed in Sweden due to high content of natural organic matter in surface water. Effective pathogen removal minimizes the need for disinfection. For groundwater, disinfection is often not used. Swedish DWTPs follow a new trend where less disinfection is used, especially disinfection with chlorine, even though the dosage is low in relation to the levels applied internationally. Instead, UV-light has replaced chlorine disinfection (Lindberg & Lindqvist, 2005).

### 2.1 Kungälv's Current Drinking Water Treatment Plant Today

Dösebacka is an Artificial Groundwater Recharge plant (AR-plant) that is situated along the western side of the river Göta Älv, 5 km north of Kungälv city (Figure 4). Dösebacka AR-plant supplies the



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population with 2.2 million cubic metres of drinking water annually (approximately 6 000 $m^3$/day) mainly to Kungälv and some parts of Ale municipality (Zagerholm, et al., 2007).

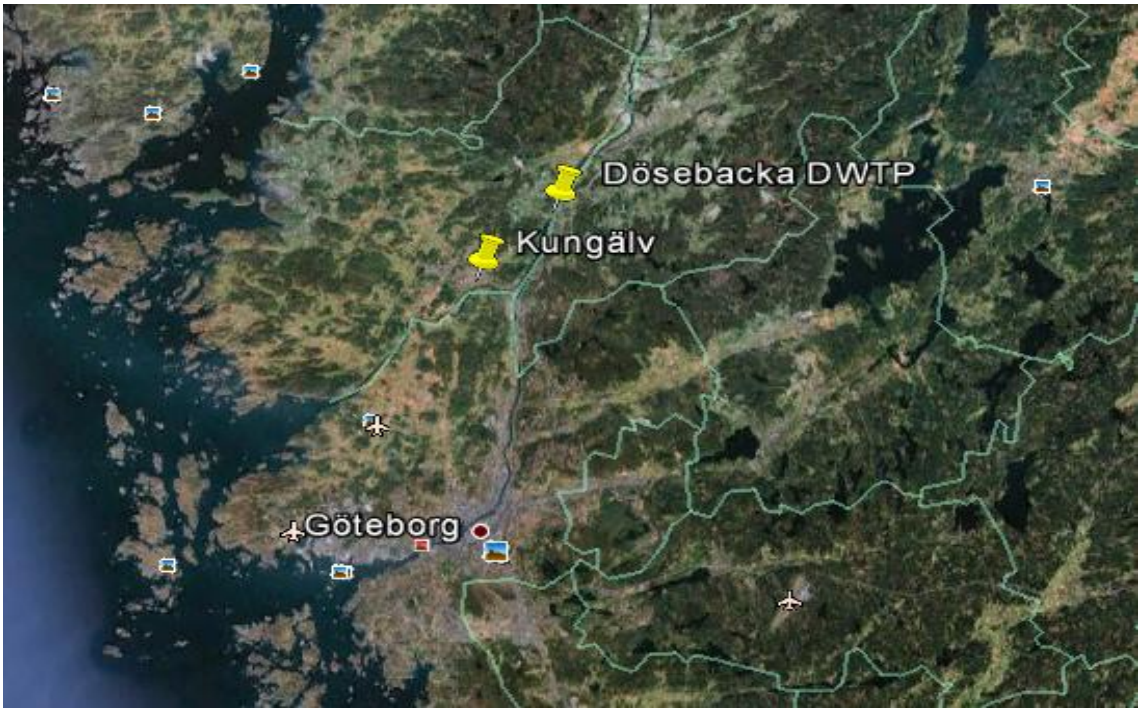


**Figure 4. Dösebacka AR-plant (Google earth, u.d.)**

The existing plant consists of one sedimentation basin, 9 infiltration basins and 15 abstraction wells (Appendix 1) shown in Figure 5. The treatment process begins with intake of surface water from Göta älv pumped to a sedimentation basin and conveyed to infiltration basins. The filtered water is then abstracted through wells and pumped to two reservoirs. Water abstracted in two wells exhibits very high turbidity and undergoes additional treatment by chemical precipitation using aluminium sulphate and filtration. Before the distribution from the reservoirs, the water pH is adjusted to prevent pipe corrosion. The treated water shows low microbial content, but uses chlorination to treat the water when necessary (EU, 2002).



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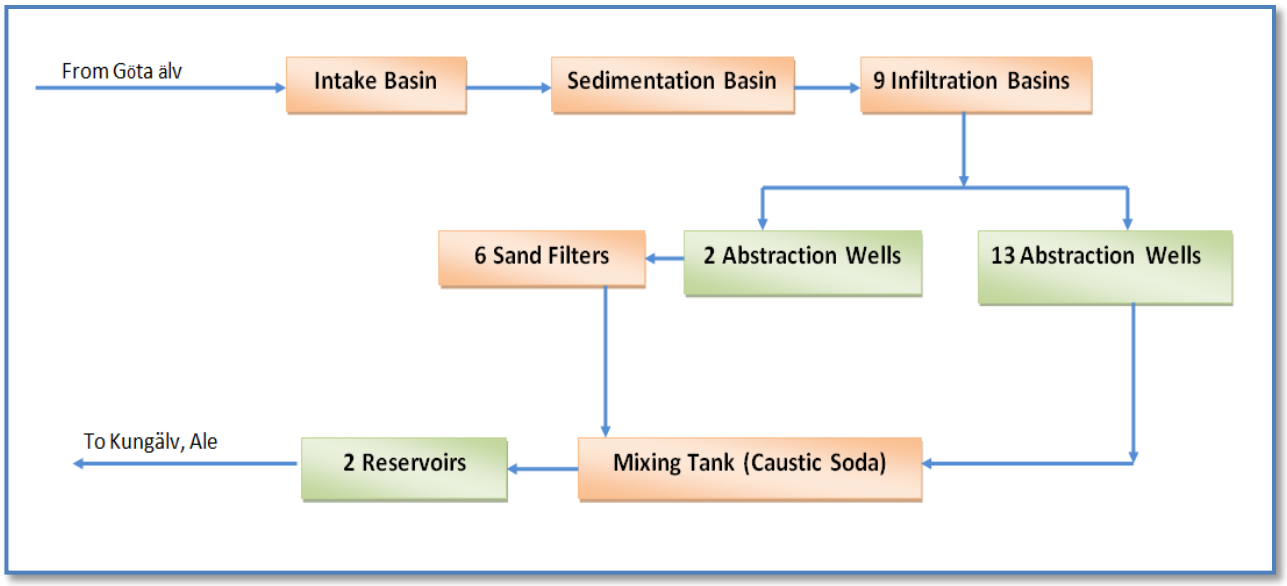


**Figure 5. Process diagram of current treatment plant (EU, 2002)**

***Sedimentation Basin***

Sedimentation basins are large tanks where water flows slowly to promote the sedimentation of particles.

***Infiltration basins***

In infiltration basins, water is percolated over a period of days through biologically and chemically active soil environment (Appendix 1, Figure 14). The soil environment reduces nutrient loads in water through nitrification/denitrification reactions, adsorption reactions to reduce phosphorus and filtration to remove suspended particles (Sumner & Bradner, 1996). The unsaturated zone is the most effective in the treatment of the water and Dösebacka unsaturated zone varies between 0 to 7.7 m (EU, 2002). The infiltration basins have a total area of 12 000 $m^2$ and have an elevation 2 to 3 meters higher than the ground level at the abstraction wells that are located 100 to 150 meters from the basins (Zagerholm, et al., 2007).

The infiltrated water is received in abstraction wells that are placed as close as possible to the Göta älv shore in order for the water to spend longer duration in the aquifer. According to Zagerholm et al, the average duration of water in the aquifer (from dam F to the intake well GRP9) is approximately 250 hours or 10 days (Zagerholm, et al., 2007).

***Sand Filters***

Sand filters contain porous media through which water passes and particulate matter captured (SDWF, 2012). The water from abstraction wells number 9 and 11 in Dösebacka is turbid and therefore aluminium sulphate is added to reduce the turbidity through coagulation and flocculation. The flocs formed and other suspended particles are then removed by sand filtration.

## 2.2 The New Proposed Drinking Water Treatment Plant

The proposed treatment plant for Kungälv municipality designed by Norconsult consists of today's artificial recharge plant upgraded with surface water and groundwater treatment processes. The treatment plant is categorised as a surface water treatment plant and a groundwater treatment plant. The



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surface water treatment processes include screening, micro-straining, chemical precipitation, rapid filtration (DynaSand filters) and carbon filtration to reduce the amount of suspended particles e.g. natural organic matter (NOM) and increase the infiltration capacity. The groundwater treatment processes include infiltration followed by oxidation, rapid sand filtration and UV-disinfection. These processes are planned to fulfil the health based targets in regarding waterborne pathogens. The proposed treatment system is conceptually illustrated (Figure 6) below.

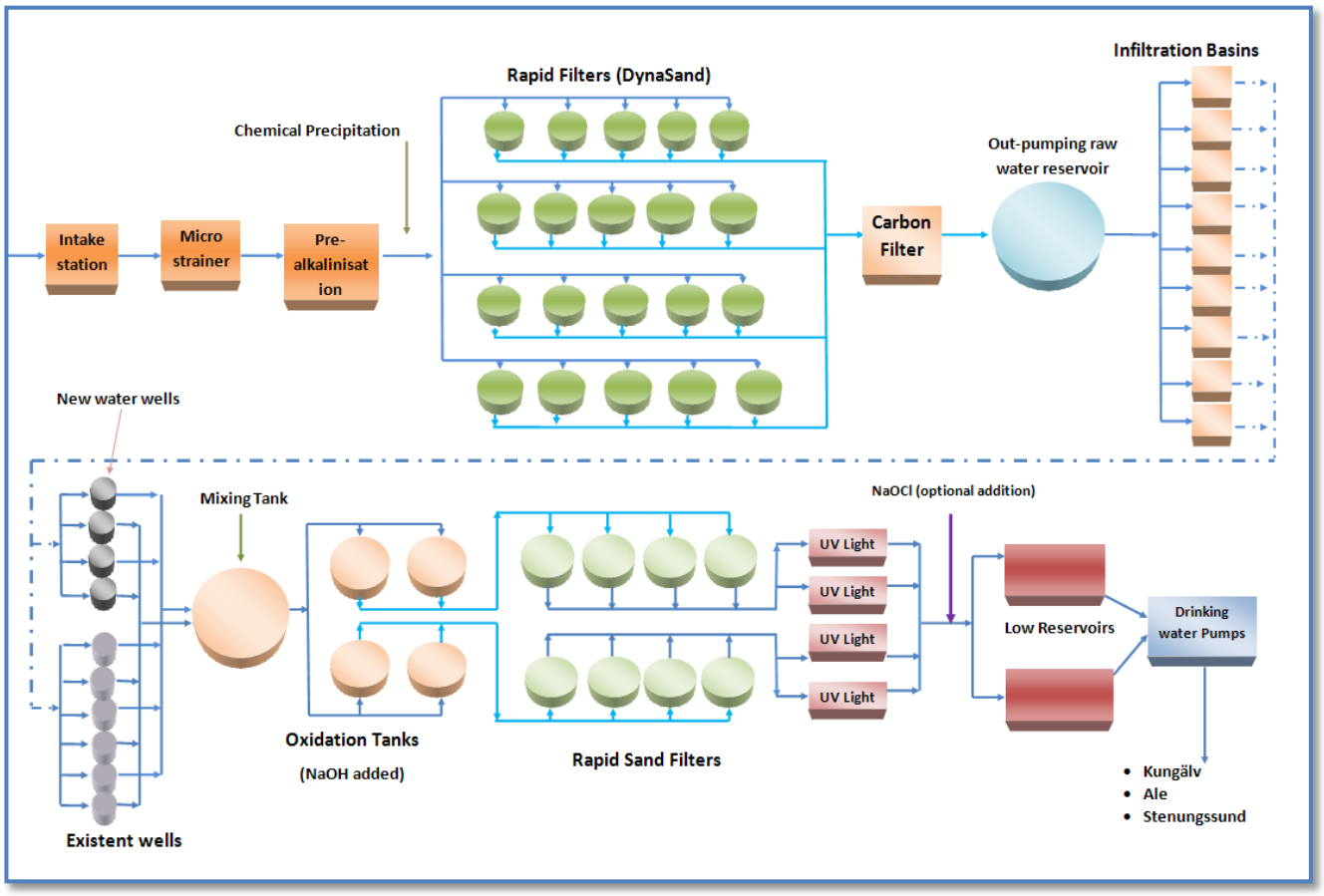


**Figure 6. Conceptual Model of the proposed water treatment plant (Norconsult, 2011)**

### 2.2.1. New surface water treatment plant

***Screening and micro- straining***

Two screens are installed at the intake at Göta älv to prevent debris and large particles from reaching the intake pipes and the pumping station (capacity of 830$m^3$/h). Water is extracted at a flow rate of 0.2$m^3$/s. The first treatment barrier after abstraction is micro-straining and the strainers have a pore size of approximately 60 µm. The purpose of micro-strainers is to remove algal cells, fractions of protozoa and reduce the quantity of coagulant required for further removal of suspended materials (LeChevallier & Keung Au, 2004).

***Pre-alkalinisation and chemical precipitation***

After micro straining, pre-alkalinisation follows, here chalk or lime is used to adjust the total hardness, total alkalinity and pH, to act as a buffer to keep the pH constant. This is followed by chemical precipitation where dissolved NOM and (ionic) metals are removed by conversion to insoluble particles by chemical reaction (Water Specialists Technologies, 2009). The chemical used in this process is Polyaluminum Chloride (PAC) which is added at the water inflow to the rapid filters. Chemical precipitation for the proposed treatment system refers only to coagulation which promotes the interaction of small particles to form larger particles known as flocs (LeChevallier & Keung Au, 2004).

***Rapid Filtration (DynaSand filters)***

Filtration is the process of removing suspended solids from water passing through a permeable membrane or porous bed of materials. Rapid sand filters (DynaSand type) are the proposed filtration type for this system. The precipitation and aggregation of particles occurs in the filtration beds where the flocs are removed. This filtration is therefore a type of conventional treatment called direct filtration (preceded by chemical coagulation) or in-line filtration (Smeets, et al., 2006). After filtration water passes by gravity to a reservoir placed under the DynaSand filters. This reservoir has a capacity of 320 $m^3$and from here the water is pumped to the groundwater treatment plant. Direct filtration will consist of four lines with five DynaSand filters each making a total of 20 filters but with plans to increase to six lines (30 DynaSand filters ) later on (Norconsult, 2011).

***Carbon filtration***

Activated carbon is a water filtration method where chemicals are attracted or adsorbed to the filter media. This filter is effective in removing organic contaminants (trihalomethanes, pesticides and industrial solvents) from water but not that effective in removing microbes, sodium, nitrates and fluorides. Carbon filtration is also used to generally improve aesthetic aspects of the water such as taste and odour (LabWater, 2012). The carbon filtration, the water is temporarily stored in a raw water reservoir.

**2.2.2. Groundwater treatment plant**

***Infiltration basins and abstraction wells***

The filtered water from the reservoirs in the surface treatment plant is then conveyed to the infiltration basins (see infiltration in section 2.1), percolated to the abstraction wells where it is pumped to a mixing tank prior to oxidation tanks. The proposed system will retain six of the existing wells and four new ones will be constructed (Norconsult, 2011).

***Oxidation***

Oxidation is the interaction of oxygen molecules and different substances they come in contact with. Water is oxidised by aeration (air and water contact) and the purpose of this aeration is to reduce carbon dioxide, to oxidise iron and manganese found in many well waters and to reduce ammonia and hydrogen sulphides (Water & Process Technologies, 2012). The infiltrated water from the wells is pumped to oxidation tanks where aeration takes place and sodium hydroxide is added to adjust the pH. The plant will have a total of five oxidation tanks, one tank used for mixing the water from the wells to obtain an even water quality and the rest of the tanks placed in two parallel lines through which the flow is divided.



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***Rapid filtration***

The oxidised water flows by gravity to rapid sand filters and undergoes separation of the suspended particles from water. The water is filtered through a total of eight rapid sand filters in two parallel lines.

***UV disinfection***

Disinfection kills or inactivates pathogens in water supply to ensure that water is safe to drink. UV disinfection is the use of ultraviolet light to kill or hinder growth of pathogens in water. UV light penetrates the cell walls of an organism and disrupts the genetic material, hence making reproduction impossible and completely destroying the bacteria (Tech Brief, 2000). After the conventional filtration, the water will be disinfected by UV-lights and finally will undergo the last pH adjustment.

The treatment plant also includes a chlorination system that will use Sodium hypochlorite (NaOCI) as the disinfectant if extra disinfection is needed. The treated water is stored in two reservoirs with a capacity of 5000 $m^3$ before distribution.



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# 3. Microorganisms

Microorganisms are a diverse group of unicellular or simple multi-cellular organisms. Water is habitat for many types of microorganisms, some of which are advantageous in their ability to degrade pollutants in water. However, other microorganisms cause illness and can even be life threatening. These disease causing microorganisms (pathogens) therefore become contaminants of drinking water.

## 3.1 Waterborne pathogenic microorganisms

Pathogenic microorganisms likely to cause waterborne diseases are mainly categorised as bacteria, viruses and protozoa and those most commonly concerning water supplies have been listed by the World Health Organisation –WHO (Appendix 1). This study takes into account eight types of pathogens falling in the three categories below (Table 1) because they are considered most likely to cause waterborne disease outbreaks in Sweden. These pathogen categories are also a risk because of their persistence in colder waters and their resistance to chlorination (Svensk Vatten Utveckling, 2007).

**Table 1. Waterborne pathogens and their significance a in water supply (WHO, 2008)**

| Pathogen | | Persistence in water supplies | Relative infectivity | Resistance to chlorine | Important animal source |
|---|---|---|---|---|---|
| Bacteria | *Campylobacter* | Moderate | Moderate | Low | Yes |
| | *Salmonella* | Moderate | Low | Low | No |
| | EHEC | Moderate | High | Low | Yes |
| Viruses | Adenovirus | Long | High | Moderate | No |
| | Norovirus | Long | High | Moderate | No |
| | Rotavirus | Long | High | Moderate | No |
| Parasites | *Cryptosporidium* | Long | High | High | Yes |
| | *Giardia* | Moderate | High | High | Yes |

### 3.1.1 Bacteria

Bacteria are unicellular organisms that are present in every environment. They have widely varying properties and are capable of producing and consuming a variety of organic and inorganic matters. Almost every bacterium except some aquatic bacteria is sensitive to chlorination (Lundberg Abrahamsson, et al., 2009).

***Campylobacter***

Campylobacter can be found in both humans and animals, mostly in birds and can cause zoonotic infection i.e. it is able to transmit between human and animals (SMI, 2010). They survive for a few hours in environments at temperatures greater than 30 $^{o}$C but can last several days at temperatures lower than 4 $^{o}$C. Campylobacter has a low critical dose (800 – 100 000 ingested organisms) which means that at low level it can cause infection and possible disease. Infection of humans is usually characterised by diarrhoea, fever and abdominal cramps. Campylobacter infection may lead to severe but rare sequelae including arthritis (Hörman, 2005). Campylobacter is the most diagnosed microorganism in Sweden responsible for waterborne outbreaks. Since 1980, 20 waterborne outbreaks of campylobacter have been reported with at least 2 000 infected individuals reported within the four major incidents. Due to



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lack of direct correlation between water-quality and conventional indicator organisms, the chance of finding the source of an outbreak is difficult (SMI, 2010).

***Salmonella***

Salmonella is widely found in nature and is present in most warm-blooded animal populations. Salmonella causes intestinal infection and one strain particular to humans causes typhoid fever. is Salmonella bacteria which also causes Salmonellosis, has over 2500 known serotypes through consumption of contaminated food and water. Its symptoms include fever, abdominal pain, diarrhoea, nausea and sometimes vomiting. It is especially dangerous to children and elderly causing dehydration and bloodstream infections (WHO, 2011). It has been noted that surface runoff contributes to Salmonella load in surface waters. This microorganism can reach the aquatic environment via the faeces of infected humans or animals through sewage discharge or runoff from agricultural areas (Levantesi, et al., 2011).

***Enterohaemorrhagic Escherischia coli (*EHEC*)***

*Escherichia coli* (*E.coli*) is commonly found in the intestinal tract of humans and warm-blooded animals. While most *E.coli* species are harmless, some species cause gastrointestinal disease. *E.coli* is categorized into seven groups including *Enterohaemorrhagic Escherichia coli* (EHEC) related to the 0157:H7 serotype. This strain of *E.coli* has been linked to outbreaks of waterborne diseases. *E.coli* is transmitted mainly by faecal-oral route either through contaminated water and food or direct contact (AWWA, 2006). Symptoms of diseases caused by EHEC include abdominal cramps and diarrhoea that may proceed to bloody diarrhoea (haemorrhagic colitis) especially in children. Incubation period ranges from 3 – 4 days and infection may last for 10 days (WHO, 2011).

### 3.1.2 Viruses

In contrast to other cells, viruses are not able to metabolize on their own but instead require other organisms as host for their survival and reproduction. Viruses are characterised by their stability and their ability to infect all cells including microorganisms. Due to their small size (smallest known virus has a diameter of 10 nm), an accurate estimation of virus concentrations in water courses and their risk level of infection are difficult to obtain. (Madigan & Martinko, 2006).More than 100 different types of enteric viruses have been identified in human faeces (Appendix1) and the ones common to Sweden has been considered for this study (Table 2). It has been observed that the number of viruses excreted by humans may be more than one million per gram of faeces and a concentration of 500 000 infectious virus particles per litre of raw sewage has been detected in some parts of the world (Joseph, et al., 1978). At the water treatment facilities, a chain of treatment processes in combination will reduce the number of viruses either through physical removal barriers or barriers that provide inactivation and destruction. The conventional removal treatment process includes coagulation, flocculation, sedimentation and filtration. Destruction processes include inactivation in the presence of high pH, chemical oxidation by disinfectants and photo-oxidation by use of specific dyes combined with lights (Joseph, et al., 1978).

Due to the lack of knowledge about viruses as live microorganisms and standardized analysis methods, no requirements in terms of $\log_{10}$-reduction or inactivation are recommended for the treatment processes of wastewater (Lundberg Abrahamsson, et al., 2009).



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***Norovirus***

Norovirus are small ribonucleic acid (RNA) viruses with a high degree of genomic plasticity and capability to adapt to new environments. About 20 genotypes of Norovirus have been recognised and because of their wide inherent genetic variability are divided into five genogroups. Genogroups I and II (GI and GII) are responsible for human infection. Symptoms of Norovirus infections are typified by violent vomiting, high fever, diarrhoea, and headache. The infective dose for man is very low at about 10 – 100 virus particles, with an incubation period of 1-3 days, and remaining infective for 2-3 weeks (Hörman, 2005). Norovirus (GII) is the main reason for winter vomiting disease in Sweden which is infectious and is transmitted through person to person contact, contaminated water and contaminated food. (Lund & Lindqvist, 2004).

***Rotavirus***

Rotaviruses are non-enveloped, double-stranded RNA viruses belonging to the family Reoviridae. These viruses have been divided into six groups, three of which infect human (groups A, B and C) s. In general, rotaviruses cause gastroenteritis, including vomiting and diarrhoea. The severity of the gastroenteritis can range from mild to severe and in some cases is fatal. In young children, extra-intestinal manifestations, such as respiratory symptoms and seizures can occur. The incubation period is about 4–7 days and the illness generally lasts between 5 and 8 days. Theoretically, a single infectious virus particle is capable of causing infection; although more than one infectious virus particle is generally required (median infectious dose for rotavirus is 5.6) (Health Canada, 2010).

***Adenovirus***

Adenoviruses are members of the Adenoviridae family containing double-stranded DNA. At present, there are 51 serotypes of adenoviruses; about 30 % of these are pathogenic in humans, most causing upper respiratory tract infections. Serotypes 40 and 41 are the cause of the majority of adenovirus-related gastroenteritis. Symptoms of adenovirus gastroenteritis include diarrhoea and vomiting. Adenoviruses are a common cause of acute viral gastroenteritis in children. Infections are generally confined to children less than 5 years of age and are rare in adults. The incubation period lasts 3 –10 days, and illness may last a week. The viral load in faeces of infected individuals is approximately 108 particles/g of faecal matter. This aids in transmission via the faecal–oral route, either through direct contact with contaminated objects or through recreational water and, potentially, drinking water (Health Canada, 2010).

**Table 2. Virus types common in Sweden and the infection caused**

| Virus group | Number of types | Disease or sign caused |
|---|---|---|
| Rotavirus (Reovirus family) | 3 | Epidemic vomiting and diarrhoea, mainly to children |
| Adenovirus | > 30 | Respiratory disease, eye infections |
| Norovirus | 20 | Violent vomiting, high fever, diarrhoea, and headache |



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### 3.1.3 Protozoa

Protozoa are a group of unicellular eukaryotic microorganisms without cell walls. They are colourless, motile and are larger than other comparable microorganisms like Prokaryotes that do not have a membrane-bound nucleus but their genetic information is in circular loop called a plasmid. Protozoa are found in all types of aquatic environment and can grow in soil and in aerial habitats such as on the surface of trees. Most of the protozoa are parasitic and can be found in both humans and animals. Further, some species are zoonotic i.e can be transmitted from humans to animals (Madigan & Martinko, 2006). Protozoa thrive in cold water while indicator organisms like *E.coli* do not and therefore are difficult to detect by indicator organisms. Protozoa are resistant to disinfectants especially chlorination within the dosage that is usually recommended for drinking water treatment plants - DWTP (SVU, SMI, Livsmedelsverket, u.d.).

In order to obtain safe drinking water, it is recommended that all water utilities suspect that all surface waters might contain the protozoan pathogens Cryptosporidium and Giardia and use this as a basis for planning and designing the treatment barriers (AWWA, 2006).

***Cryptosporidium***

It is estimated that *Cryptosporidium* has 20 species of which *C. parvum* and *C. hominisare* the most noted human enteropathogens. *Cryptosporidium parvum* is divided into genotypes 1 and 2 affecting humans and cattle respectively. Symptoms of cryptosporidiosis include diarrhoea, loose or watery stools, stomach cramps and a slight fever. Some infected persons show no symptoms. The incubation period is between 2 – 10 days and infection lasts two weeks (Hörman, 2005). Testing for *Cryptosporidium* is done by detecting oocysts. The oocysts are inactivated by freezing at -15 $^{o}$C for 8 hours. Increasing water temperature to 64.2 $^{o}$C for two minutes or longer makes *Cryptosporidium* non-infectious. Oocysts also become sensitive to drying after 4 hours when they are exposed to temperatures from 18 - 28$^{o}$C (AWWA, 2006). *Cryptosporidium* enters water mainly through surface runoff from agricultural and pasture lands but also through sewage discharge.

***Giardia***

*Giardia* comprises six species that can infect a variety of hosts. *Giardia duodenalis* is infectious to humans but can infect other hosts too. Clinical infection is referred to as giardiasis and symptoms vary from severe diarrhoea to malabsorption (foul-smelling diarrhoea, abdominal pain, bloating, and nausea). Giardiasis may become chronic and illness may last for months. The incubation period ranges from 1 - 14 days and illness usually lasts 1 – 3 days (Hörman, 2005).

## 3.2 Faecal indicator organisms

Methodological and interpretation limitations are still a concern for pathogen detection and monitoring in water. These limitations include the need for specialised laboratory equipment and highly trained personnel, the high cost of analysis, the need to determine which pathogens to test for and the number of pathogens present that may vary over time and space. Because of these limitations, routine monitoring of pathogens is not practical. However there are some organisms that can be routinely monitored and can be used as indicators for faecal contamination and the potential presence of enteric viruses. The indicators commonly used include *E.coli*, enterococci, *Clostridium perfringens* spores, and viruses of bacteria (bacteriophages). Total coliforms can also be used to provide a general overview of the water quality even if it is not used to indicate faecal pollution (Health Canada, 2010).



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The use of faecal indicators helps in the estimation of the microbiological quality of drinking water by reducing the complexity and cost of a direct analysis of pathogens (Åström, 2011). The World Health Organisation however recommends that specific criteria should be followed when determining and using faecal indicator organisms. The criteria for indicator selection can include;

- General existence of the organisms in the faeces of humans and animals,
- Ability to multiply in natural waters,
- Same persistence properties in water as the faecal pathogens,
- Presence in higher numbers compared to the pathogens and responding similarly to treatment barriers as pathogens (WHO, 2008)

The relationships between indicator organisms and the presence of pathogens in surface water sources have been investigated by several studies worldwide. *Escherichia coli* (*E.coli*) and *Clostridium perfringens* have been linked to the presence of pathogens caused by faecal contamination. Bacteriophages have also been related with the presence of enteric viruses. There are however some studies that have shown no correlation between indicators and pathogens. The most suitable indicator therefore depends on the surface water source and the site-specific faecal pollution inputs (Health Canada, 2010).

*E.coli* and total coliforms have been used to verify the quality of drinking water. The presence or absence of E.coli does not strictly indicate presence or absence of pathogens. However, if the quality is monitored from the source to tap and each barrier in the drinking water system has been controlled to ensure proper operation, the presence or absence of *E.coli* and total coliform can be used as verification for whether the water is adequately treated (acceptable microbiological quality) (Health Canada, 2010) and (Livsmedelsverket, 2001).

## 3.3 Water quality and health target

Health targets are benchmarks to assist water suppliers to set up certain interventions in regard to source protection and treatment processes in order to provide safe drinking water. An accurate health target is dependent on local conditions including economic, environmental, and social/ cultural conditions, and financial, technical and institutional resources. Health-based targets for microbial pathogens reflect both control challenges, health hazards and other relevant data associated to a group of pathogens (WHO, 2008).

These targets are developed with regard to the microbial contaminant levels in water which would pose "acceptably low" risks of water borne infections to humans (Signor & Ashbolt, 2009). The World Health Organisation reference level of risk in relation to waterborne disease outbreak (the maximum frequency of infection, diarrheal disease or cancer incidence in terms of DALYs) is $1\times10^{-6}$ or one micro DALY (WHO, 2008). The commonly adopted benchmark is one used by the USEPA, which requires that the probability of an individual becoming infected by any type of reference waterborne pathogen following independent drinking water exposures over a year should not exceed $1 \times 10^{-4}$." (Signor & Ashbolt, 2009).

In Sweden, drinking water quality is controlled by the National Food Administration (Livsmedelsverket). Drinking water quality is deemed either suitable or not when samples taken at



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discharge point from the DWTP (effluent drinking water) and at the consumers tap are compared to the guideline value. The guideline values that separate the suitable drinking water from unsuitable are listed in Appendix 1. Swedish water utilities use USEPA guideline values to evaluate the efficiency of DWTPs and estimate the infection rate among population due to unsuitable drinking water.



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# 4. Material and Methods

The aim of the study was to investigate the treatment processes being recommended for the proposed treatment plant. This required evaluating the efficiency of the treatment processes and the tool used in this study is a Quantitative Microbiological Risk Assessment (QMRA) tool. The study also used mathematical formulations to estimate pathogen concentrations in the raw water and the annual infection risks today as well as in future.

The assessment of the new treatment system using QMRA was conducted using scenarios to determine the probability of infection to water consumers. Scenario zero, where infection risk is analysed using standard pathogens concentrations in the raw water estimated in the Swedish QMRA manual was studied together with three other scenarios described in sections 4.4, 4.5 and 4.6. In this study, both the current treatment plant and the new treatment system (scenario1) were considered.

## 4.1 QMRA methodology

QMRA is a methodology to quantify the risk of infection to drinking water consumers due to waterborne pathogen concentration in the source water. The Swedish Water & Wastewater Association has developed a QMRA tool which was used in this study. The methodology is based on four steps: hazard identification, dose-response formulation (effect assessment), exposure assessment and risk characterization (Figure 7) (Medema & Ashbolt, 2006).

Performing a QMR investigates if the water supply system meets the health based target. In this study the USEPA guideline value is used with an annual infection probability not exceeding $1 \times 10^{-4}$ which is one person infected out of 10 000 people exposed. This type of analysis gives a water supplier the opportunity to investigate if the water supply system (raw water quality and efficiency of the treatment barriers) under various circumstances and estimates the potential infection risks. Elimination of risks can be done by implementing risk reducing measures such as optimization of treatment processes and implement additional controls such as on-line monitoring systems (Medema & Ashbolt, 2006).



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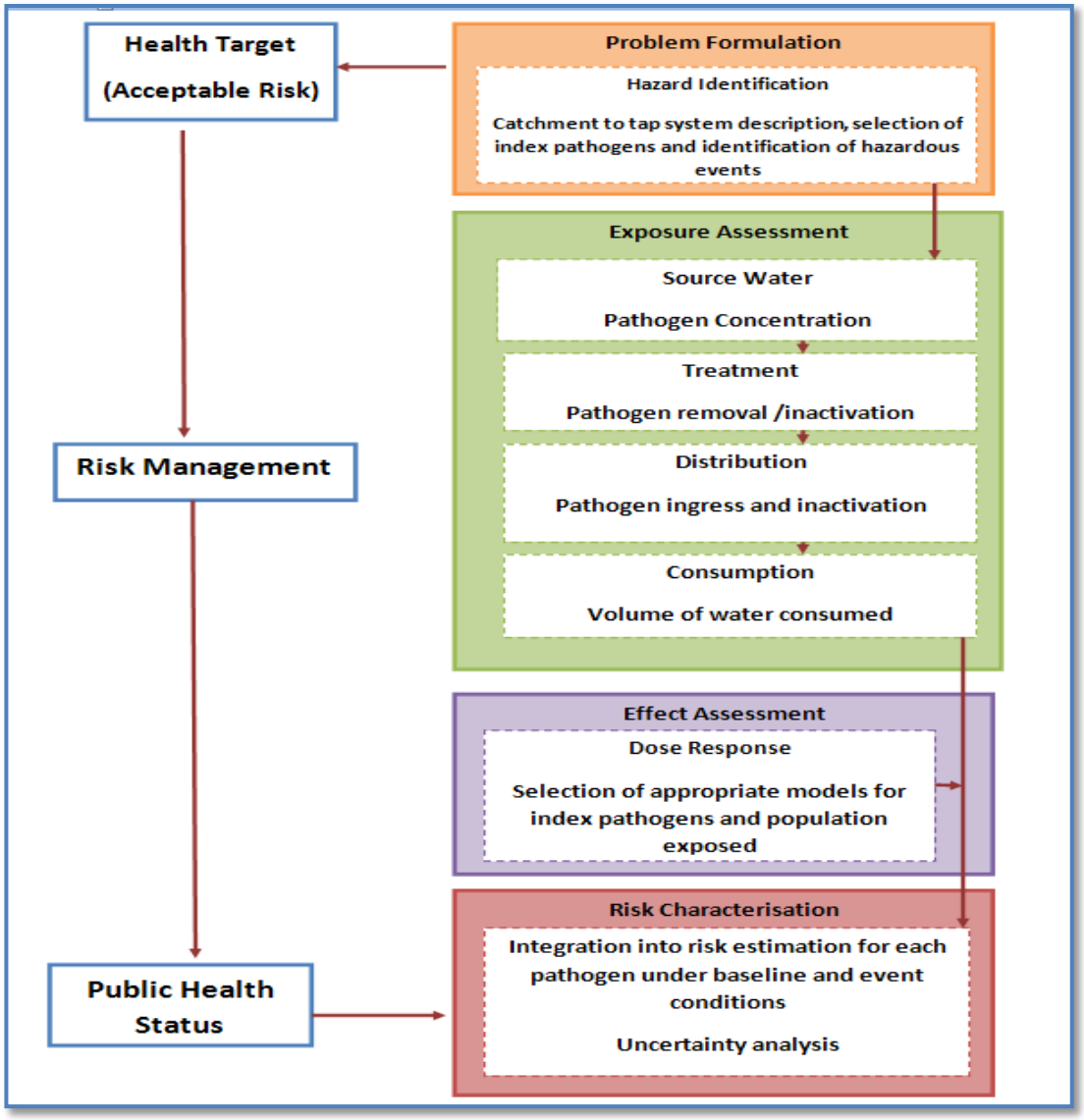


**Figure 7. Framework for the Microbial Risk Assessment in four steps (Medema & Ashbolt, 2006)**

### 4.1.1 QMRA input data

The proposed treatment system (plant) has several microbial barriers (processes), suggested as presented in Figure 5, and four of the processes were focused on in this study. These are direct filtration (Dynasand), infiltration basins, rapid sand filters, and UV-light disinfection. The micro-strainers and carbon filters were not included in the QMRA model since they are not considered as microbial barriers and have negligible effect in removing pathogens. The chemical disinfection (chlorination) process is not included in the main QMRA model because UV-light is assumed to be effectively in inactivating pathogens. However chlorination is studied in one scenario but will only be used in case of emergencies e.g. when a pathogen outbreak occurs among populations in upstream wastewater systems and the wastewater overflows into in the source. This is then compared in to situation without chlorination.

***Removal efficiency***

In the QMRA model, the removal efficiency ($log_{10}$-reduction) for each treatment process has to be defined and is formulated with triangular distribution (Appendix 1). In Table 3, the estimated log-



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removal is presented for each barrier. The removal efficiency of the Dösebacka infiltration basins was calculated based on literature for all pathogens. The $log_{10}$-reduction was set similar as for slow sand filters but was combined with literature data on removal efficiency addition per depth of the unsaturated zone. The additional removal efficiency due to the unsaturated zone was estimated as 0.5 $log_{10}$ units per metre [1](Appendix 1).

The removal efficiency of 20 Dynasand filters was used in the model although there is a proposal to increase the number to 30 according to Norconsult. The reason for using 20 instead of 30 is that if the system passes the USEPA guideline value (Annual infection risk < $10^{-4}$) with the lower number of filters, it can manage an even better result with an increased number of filters.

**Table 3. Removal efficiency ($log_{10}$-reduction) for the treatment processes studied and other input data in the MRA model**

| Treatment barrier | Number of parallel lines | $Log_{10}$-reduction | | |
|---|---|---|---|---|
| | | Bacteria | Virus | Protozoa |
| Direct filtration [a] | 20 | Triangular (1,2.1,3.4) | Triangular (1.2,3.0,5.3) | Triangular (1.4,3.2,5.5) |
| Infiltration basins | 9 | Triangular (1.2,4.6,6.7) | Triangular (0.6,4,6) | Triangular [C] (0.3,5.7,8.4) Triangular [G](1.2,5,8) |
| Rapid sand filter [a] | 8 | Triangular (0.1,0.6,1.5) | Triangular (0.1,0.8,3.8) | Triangular [C](0,2,3.1) Triangular [G](0,1.7,6.5) |
| UV-light | 4 UV-lights | Fluence dose=(40mJ/cm$^2$)[b] | | |

[a] (Smeets, et al., 2006). [b] (Stanfield, et al., u.d.). [C] *Cryptosporidium* [G]*Giardia*

***Calculated (estimated) pathogen concentrations***

In order to estimate the annual infection risk of pathogens passing through the treatment barriers, the pathogen concentrations in the raw water source need to be known. Pathogen concentrations based on measurements and calculated (estimated) values were applied. Moreover, standard pathogen concentrations from the Swedish QMRA manual were used in scenario zero which contains an estimation of annual infection risks for the current and new treatment plant (scenario 1) respectively.

Data of measured protozoa concentrations in Göta älv was available (Appendix 2) but measured values for bacteria and viruses were not available. The concentrations of bacteria and viruses were therefore calculated using equation (2) below (Åström, et al., 2011).

$$P = p.\frac{P_f}{I_f}.I_d \qquad (2)$$

$P = The\ pathogen\ content\ in\ the\ source$

$p = Risk\ level(Portion\ of\ people\ being\ infected\ in\ a\ specific\ moment)$

[1] The value was estimated from discussions with Madelane Forss from Norconsults.



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$P_f = Pathogen\ content\ in\ fresh\ faecal\ material\ from\ an\ infected\ person$

$I_f = Indicator\ organism\ content\ in\ fresh\ faecal\ material$

$I_d = Indicator\ organism\ content\ in\ source\ water(Göta\ älv)$

The contents of studied bacteria, virus and *E.coli* in fresh faecal material are presented in Table 4.

**Table 4. Content of pathogens and indicator organism *E.coli* in faecal material of infected persons**

| Pathogen | Range (Median) | Reference |
|---|---|---|
| *Campylobacter* | $10^6$-$10^9$ ($55.10^6$) | (Guillermo, et al., 1996) |
| EHEC | $10^7$- $10^8$ ($55.10^6$) | (Klein, et al., 2008) |
| *Salmonella* | $10^5$-$10^7$ ($10^6$) | (Schothorst & Beckers, 1978) |
| Norovirus | $10^6$-$10^8$ ($10^7$) | (Pang, et al., 2004) |
| Adenovirus | $10^5$-$10^{11}$ ($10^8$) | (Okoh, et al., 2010) |
| Rotavirus | $10^5$-$10^{11}$ ($10^8$) | (Okoh, et al., 2010) |
| *Cryptosporidium* | $10^6$-$10^7$ ($55.10^5$) | (Gerba, 2000) |
| *Giardia* | $10^3$-$10^8$ ($55.10^4$) | (Smittskyddsinstitutet, 2011) |
| *E.coli* | $10^6$-$10^8$ ($10^7$) | (Levy, et al., 1988) |

## 4.2 Estimation of annual infection risk

According to results from the MICRORISK project, the annual probability of infections is assumed following a binomial process which refers to a series of trials with one of two possible outcomes (infection or not infection) (Petterson, et al., 2006). This daily probability of infection for an exposed individual is expressed as $P_{inf}$ and then the daily probability of not being infected is$(1 - P_{inf})$. The probability of not being infected over a period of time can therefore be expressed as $(1 - P_{inf})^n$ where $n$ denotes the number of days, and for the annual probability of not being infected, $n = 365\ days$. The annual probability of infection risk therefore is determined using equation (3) below. The annual infection risk for one or more events occurring for a known duration (considering an expansion of the binomial model) over a year can be written as in equation (4). Equation (4) has been adjusted to suit the circumstances that have been considered for each scenario.

$$P_{Annual} = 1 - (1 - P_{inf})^{365} \quad (3)$$

$$P_{Annual} = 1 - (1 - P_{\inf\,(nom)})^{t(nom)} \prod_{n=1} \left(1 - P_{\inf(n)}\right)^{t(n)} \quad (4)$$

$P_{\inf(nom)} = The\ daily\ probability\ of\ infection\ under\ nominal(non - event)conditions$

$t(nom) = The\ days\ \ under\ nominal\ conditions$

$P_{\inf(n)} = The\ daily\ probabbility\ of\ infection\ under\ n\ different\ events$

$t(n) = Is\ days\ for\ different\ events$



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The annual risk equation is adjusted to suit the scenarios to which it is applied.

## 4.3 Current DWTP

The risk of infection for the treatment plant currently used in Kungälv was calculated using QMRA model. The pathogen concentrations considered for the current DWT plant were measured and estimated concentrations according to equation (2) and using standard concentrations from the Swedish QMRA manual (Table 6) (Lundberg Abrahamsson, et al., 2009).

***Scenario Zero***

Annual infection risks for consumers receiving drinking water from the current and new DWTPs are studied using standard concentrations given in the Swedish QMRA manual.

## 4.4 Scenario1 (Risks of infection - proposed treatment system)

Scenario 1 studies the annual infection risks if the new treatment plant were in use today. The input data QMRA model is based on measured pathogen (protozoa) concentrations during the wet and dry periods (2005 – 2011) (Bergstedt, 2012) and calculated concentrations for bacteria and virus when there is no waterborne epidemic among the population connected to upstream wastewater system. Furthermore the proposed DWT plant was tested with the standard concentration of pathogens (scenario zero) from the Swedish QMRA manual (Table 6) (Lundberg Abrahamsson, et al., 2009). Annual infection rates for Scenario 1 have been studied as four cases (1, 2, 3, and 4), when some of the treatment processes are not functioning properly, using both the measured/estimated and standard concentrations of pathogen respectively.

### 4.4.1 Pathogen concentration in Göta älv

The measured concentrations of the protozoa are shown in Appendix 2. However the concentrations for viruses and bacteria have been calculated.

***Calculated concentrations***

Using equation (2), values of an indicator organism have to be used to calculate the pathogen content in the raw water source. *E.coli* has been selected as a preferred indicator organism in this study to estimate the pathogen concentrations. *E.coli* is the most commonly used indicator for water.

The median concentrations of pathogens in faecal material ($P_f$) derived from Table 4 have been used in equation (2). The median concentration of *E.coli* measured in Göta älv ($I_d$) for four years period has been used (Table 5). The risk level ($p$) was assumed to be equal to 0.2 % that is to say that 0.2% of the population connected to the upstream wastewater system is infected, providing the normal pathogen concentration in the source water (Ander & Forss, 2011). The estimated bacteria and virus concentrations are presented in Appendix 2 and the average calculated pathogen concentrations in Göta älv is shown in Table 6.



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**Table 5. Measured median concentration of *E.coli* in Göta älv**

| Year | Median Concentration (CFU/100ml) | Reference |
|---|---|---|
| 2002 | 90 | (Kärrman, et al., 2004) |
| 2003 | 86 | (GÖTA ÄLVS VATTENVÅRDSFÖRBUND, 2003) |
| 2004 | 98 | (GÖTA ÄLVS VATTENVÅRDSFÖRBUND, 2004) |
| 2005 | 74 | (GÖTA ÄLVS VATTENVÅRDFÖRBUND, 2005) |

***Measured concentrations***

The measured concentrations of the protozoa *Cryptosporidium* and *Giardia* in Göta älv (Appendix 2) are 2005 to 2011 (Bergstedt, 2012). Moreover, standard concentrations (constant and mean values) used in scenario zero for the new treatment system are presented in Table 6.

**Table 6. Average concentration of pathogens in Göta älv**

| Pathogen | Average concentration per litre[1] | | Standard concentrations[2] |
|---|---|---|---|
| *Campylobacter* | 9.57 | Calculated concentrations | 1 (constant value) |
| EHEC | 9.57 | | 0.1(constant value) |
| *Salmonella* | 0.17 | | 1 (constant value) |
| Norovirus | 1.74 | | 1 (constant value) |
| Adenovirus | 17.4 | | 1 (constant value) |
| Rotavirus | 17.4 | | 1 (mean) |
| *Cryptosporidium* | 0.04 | Measured concentrations | 0.4 (mean) |
| *Giardia* | 0.04 | | 0.5 (constant value) |

[1]*Both measured (protozoa) and estimated concentrations (bacteria and virus).* [2]*From the Swedish QMRA manual* (Lundberg Abrahamsson, et al., 2009)

Due to variability of input data in the QMRA model, probability density function (PDF) was used to describe the variability of the water quality with time depending on catchment activity, seasonal climate variation and point source contamination such as CSOs. The Gamma distribution was chosen to describe the variability of pathogen concentrations. The parameters for the Gamma distribution for all pathogens are presented in Appendix 2. The standard concentration (during normal situations) of pathogens is expressed as a lognormal distribution as reported in the Swedish QMRA manual with parameters described in more detail in Appendix 2.

***Annual infection risk calculation***

The annual infection risk for all pathogens in scenario one when the new drinking water treatment plant was tested with the measured and calculated concentrations was collected from the QMRA model. In scenario zero, when the proposed DWT plant was tested with the standard concentrations (normal situations), the annual infection risk for all pathogens was collected directly from the QMRA model.

**4.4.2 Case 1- Annual infection risk without chlorination**

The proposed treatment processes (microbial barriers) except chlorination (not operating) were run in the QMRA model to calculate the risk of infection. It is proposed to use chlorination only when



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pathogens are detected in the raw water. This simulation in the model helps to asses if the proposed treatment plant will be efficient without chlorination.

#### 4.4.3 Case 2- Annual infection risk with chlorination

Annual infection risk when all barriers, including chlorination are operating was determined. The purpose is to compare the pathogen removal efficiency when two disinfection barriers (UV-disinfection and chlorination) are operating

According to the Swedish National Food Administration, the chlorine dosage should not exceed 1.0 $g/m^3$ at the plant and the level of chlorine in the drinking water provided into the distribution network should not be above 0.4 mg/l (Livsmedelsverkets författningssamling, 2011).

The chemical disinfection used in the QMRA model is chlorine dioxide with a dosage of 0.4 mg/l. and has been simulated for two sub-cases. The first sub-case considers contact time based only on residence time within the distribution pipe network (no contact time in the reservoirs) and the second sub-case considers thee contact time based on residence time within both the reservoir and in the distribution pipe network (Appendix 2). The reason for this was to observe the difference on impact of chlorination in inactivating pathogens using two different contact times. Moreover this helps provide a recommendation of appropriate contact time for the chlorination to achieve optimal inactivation rate of pathogens.

#### 4.4.4 Case 3- Annual infection risk when one of the barriers is removed from the treatment plant

Annual infection risk was determined when one barrier at a time is removed from the treatment train. The barriers studied in this case are direct filtration, infiltration basins, rapid filtration and UV disinfection. This case useful not only for determining the critical link within the treatment train but also to learn which part of the treatment system to control better to prevent critical breakdowns.

The result is essential in planning and deciding treatment barriers combination, and to exclude a barrier from the treatment system in case of budget cut down in the project. The infiltration basins however are present at the current DWTP in Kungälv so this scenario may not be relevant for this barrier. However it was of interest to study the effect of removing from the treatment plant for a whole year even if that is not a realistic scenario.

#### 4.4.5 Case 4- Annual infection risk during maintenance of UV-disinfection units

The new DWTP has four UV-units for inactivation of pathogens especially protozoa. The UV-units use cleaning processes to provide the optimal removal efficiency they were designed for. Modelling the annual infection risk when two UV units are removed i.e. cleaning process activated helps to assess whether the consumers are safe from infection when maintenance is carried out. The maintenance process for both UV units was considered to take in average five days during a year. This maintenance operation was adjusted to suboptimal operation (two UV units operating below the design level) in the QMRA model and thus two UV disinfection units operate normally.

The annual infection risk for viruses, bacteria and protozoa was calculated using equation (5) below adopted from the generic equation (4). The daily infection risks for normal condition and the sub-optimal risk used in equation (5) are obtained from the QMRA results for case 1 and model simulations with two UV-units respectively.



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$$P_{Annual} = 1 - \left( \left(1 - P_{daily,normal}\right)^{t_{normal}} . (1 - P_{daily,suboptimal})^{t_{suboptimal}} \right) \quad (5)$$

$t_{normal} = Time\ when\ UV - lights\ operate\ normally$

$t_{suboptimal} = Time\ when\ only\ two\ UV - lights\ operate$

$P_{daily,normal} = Daily\ risk\ when\ UV - lights\ operate\ normally$

$P_{daily,suboptimal} = Daily\ risk\ when\ two\ UV - lights\ operate$

In scenario zero, considering the standard concentrations, the annual infection risk for all pathogens was estimated through equation (5).

## 4.5. Scenario2 (Annual infection risk in 2060)

The buildings of the proposed plant will be designed to last about 50 years and the mechanical parts to last about 30 years. It is therefore important to find out if this system will be capable of treating water efficiently in the future. Scenario two assesses the annual infection risk for the years between now and 2060. This requires an estimation of the concentration of pathogens in Göta älv in 2060.

### 4.5.1 Pathogen concentration estimation

In order to estimate the concentration of pathogens in the year 2060, the standard pathogen concentrations given in the Swedish QMRA manual were used as a starting point. The pathogen concentrations were multiplied by an annual growth factor of 1.01 (1%) i.e. the standard concentrations from 2010 increased by 1% every year to 2060. The concentration of pathogen in the future will be affected by different factors such as precipitation, surface runoff and turbidity and can be estimated differently based on various factors (Pettersson 2012[2]). Here, the estimation of pathogen concentrations has been modelled to increase exponentially until year 2060. This is an appropriate assumption in the absence of other data for future concentration forecast. The exponential function equation (6) used for this assumption is expressed as;

$$C = C_p . 1.01^x \quad (6)$$

$x = Number\ of\ years\ from\ year\ 2010\ until\ year\ 2060$

$C = Pathogen\ concentrations\ in\ source\ water$

$C_p = Pathogen\ concentrations\ in\ source\ water\ for\ year\ 2010$

In Table 7, average concentrations that have been estimated based on the exponential equation described above are presented. The calculation is presented in more detail in Appendix 3.

[2] Based on discussion with supervisor Thomas Pettersson during a consultation



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**Table 7. Estimated average pathogen concentration 2060**

| Pathogen | Average concentration per litre |
|---|---|
| *Campylobacter* | 1.30 |
| EHEC | 0.13 |
| *Salmonella* | 1.30 |
| Norovirus | 1.30 |
| Adenovirus | 1.30 |
| Rotavirus | 1.30 |
| *Cryptosporidium* | 0.52 |
| *Giardia* | 0.65 |

The trend of estimated concentrations of pathogens from 2010 to 2060 is illustrated in Figure 8.

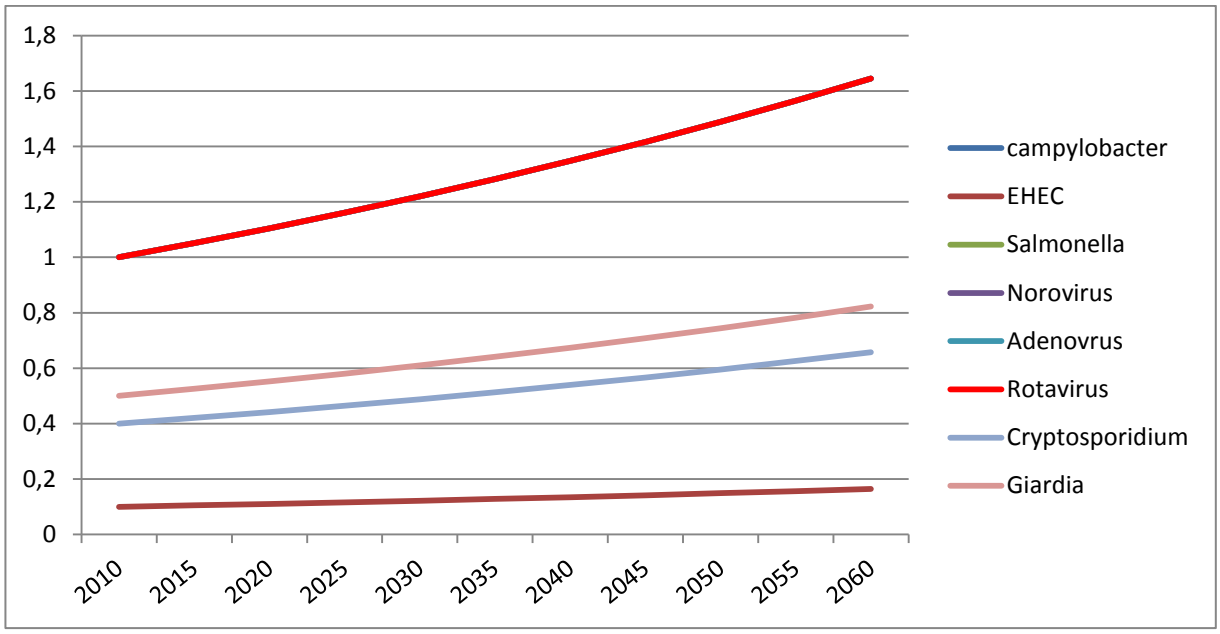


**Figure 8. Trend of pathogen concentrations in Göta älv from 2010 to 2060**

### 4.5.2. MRA model input data

The input data of the removal efficiency for the treatment barriers and other data related to the barriers that are put into the QMRA model for the second scenario (year 2060) are same as for the first scenario (Table 3). Then the estimated Gamma parameters (shape and scale) for year 2060 (Appendix 3) were added into the model and simulation for each pathogen was performed.

### 4.5.3. Estimation of annual infection risk

The annual infection risks for the second scenario (year 2060) were calculated by the QMRA model.

### 4.5.4. Pathogen removal efficiency by infiltration basins in 2060

Studies of climate change state more extreme rain events are expected in future and this may result in rising water levels. This study considered that the infiltration basins along Göta älv together with the abstraction wells could be impacted by raising groundwater levels reducing the effectiveness of pathogens removal by the unsaturated zone and deterioration of water quality at the plant.



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In case of a higher number of wet days, recharge of precipitation into the ground especially on the drumlin area which consists of permeable soil media might raise the groundwater table. This scenario is considered appropriate here to study the impact of the rising water table in reducing the unsaturated zone by 1 metre, in order to study the risk of infection when the removal efficiency of infiltration basins reduces. On the other hand, when intensive rainy days are considered, surface runoff might stress the water quality in the basins if the basins are not protected at a certain level above the ground surface. The runoff could contain pathogens from animals' faeces particularly from the forest area on the north side of the infiltration basins.

In order to estimate the risk of infection due to the rise of the groundwater table by one metre, the $\log_{10}$-reduction calculated in the QMRA model was changed. The new calculation considers an average unsaturated zone of 2.85 meters (1 meter decrease compared to the normal condition with 3.85 meters unsaturated zone) (Table 8).

The annual infection risks in the case of raised groundwater table in the infiltration basins have been calculated by the QMRA model.

**Table 8. $Log_{10}$- reduction in case of one-meter groundwater level rising in the infiltration basins**

| **Concentration** | **Bacteria** | **Virus** | **Protozoa** | |
|---|---|---|---|---|
| | | | ***Cryptosporidium*** | ***Giardia*** |
| Minimum | 1.2 | 0.6 | 0.3 | 1.2 |
| Likeliest | 4 | 3.6 | 5.2 | 4.7 |
| maximum | 6 | 5.4 | 7.9 | 7.4 |

## 4.6. Scenario 3- Waterborne outbreak in upstream town

This scenario considers that a waterborne disease outbreak of pathogens occurring upstream of Kungälv municipality. Possible sources are the cities of Lilla Edet and Trollhättan with combined sewer overflows that release wastewater to Göta älv. Such a waterborne disease outbreak on a population upstream of the Kungälv DWTP could be a source of contamination of the raw water, with a potential pathogen concentration that could infect the people in Kungälv. The concentrations of pathogens under this circumstance were estimated using equation (2). In equation (2) the risk level (p) or portion of people being infected in a specific moment has been estimated to be equal to $0.40 \times \frac{7}{75}$ which a risk level of 40% reflects an infection of 40 % of a population upstream Kungälv during a specified period.[3] The outbreak was assumed to last for a period of 2.5 months or 75 days. The number of days that a person is estimated to be infected was set to 7 days for all pathogens. Studying this scenario is useful

[3]The largest outbreak between 1980 and 1999 in Sweden occurred in early 1988 and affected approximately 11,000 people (with an attack rate of 41%) (Andersson & Bohan, 2001). In December 2011, the community of Östersund had a waterborne disease outbreak which affected 45% of the water consumers (FOI, 2012).



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when analysing how well the proposed treatment system can manage a possible outbreak contamination of raw water and what the consequences (infected individuals) would be if the treatment system fails. The consequence is compared to the USEPA guideline value. The estimated average concentrations for this scenario are presented in Table 9.

**Table 9. Average concentration of pathogens in the raw water source considering an outbreak upstream the DWTP of Kungälv**

| Pathogen | Average number of organisms per litre |
|---|---|
| *Campylobacter* | 179 |
| EHEC | 179 |
| *Salmonella* | 3.3 |
| Norovirus | 33 |
| Adenovirus | 325 |
| Rotavirus | 325 |
| *Cryptosporidium* | 18 |
| *Giardia* | 1.8 |

#### 4.6.1 Estimation of annual infection risk

The annual infection risk for bacteria, virus and protozoa is estimated by using equation (7) below:

$$P_{Annual,outbreak} = 1 - ((1 - P_{daily,normal})^{t_{normal}} . \left(1 - P_{daily,outbreak}\right)^{t_{outbreak\ event}}) \qquad (7)$$

The normal daily infection risk is the risk during normal condition (no wastewater discharge into source water from upstream outbreak population) using the QMRA result from scenario1- case 1. The daily infection during an outbreak ($P_{daily,outbreak}$) was provided from the QMRA model using the estimated pathogens concentration due to an outbreak upstream of Kungälv.



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# 5. Results

The risk assessment was performed for the current treatment system and the proposed treatment plant considering various scenarios. The results of the assessments are presented below for each scenario as annual infection risk, number of infected people and the $\log_{10}$-removal by treatment barriers.

## 5.1. Annual infection (treatment plant currently used)

In order to recommend the proposed treatment system, its annual infection risk has to be compared with the current treatment system. The treatment plant that is currently used in Kungälv was assessed regarding its effectiveness in removing pathogens in the raw water. The annual infection risks (estimated with measured/estimated concentrations) for all pathogens except *Salmonella* exceed the USEPA guideline value ($1 \times 10^{-4}$) and the risk values are shown in Table 10. If the measured and calculated pathogen concentrations in scanerio1 (Table 6) were present in the raw water source, there would be a probability of more than 1 person out of 10 000 consumers suffering symptoms of diseases except for *Salmonella*. The daily infection risk for all pathogens is presented in Appendix 2. The number of people infected is also shown in the table. The annual infection risks when the standard concentrations (scenario zero) were used are presented in the same table which shows that for all pathogens except for *Salmonella* the annual infection risk exceed the USEPA guideline value. The number of infected persons by each pathogen except for *Giardia* in the scenario zero is remarkably lower in comparison to the ones with measured and estimated concentrations.

**Table 10. Annual risk of infection of the current DWTP in Kungälv**

| Pathogen | Annual infection risk - Current DWTP[1] | Number of people infected[1] | Annual infection risk - Current DWTP[2] | Number of people infected[2] |
|---|---|---|---|---|
| *Campylobacter* | **3.00E-01** | **7 500** | **1.10E-01** | **2750** |
| EHEC | **4.50E-02** | **1 125** | **6.80E-04** | **17** |
| *Salmonella* | 3.50E-06 | 0 | **2.00E-05** | 0 |
| Norovirus | **2.60E-01** | **6 500** | **2.10E-01** | **5250** |
| Adenovirus | **4.80E-01** | **12 000** | **1.80E-01** | **4500** |
| Rotavirus | **4.90E-01** | **12 250** | **1.30E-01** | **3250** |
| *Cryptosporidium* | **1.10E-02** | **275** | **2.80E-03** | **70** |
| *Giardia* | **2.20E-04** | **6** | **3.70E-02** | **925** |

[1]*When the estimated & measured concentrations were used.* [2]*When the standard concentrations were used* (Lundberg Abrahamsson, et al., 2009)

The number of infected people due to the inefficient treatment by the current treatment plant with the measured/estimated and the standard concentrations at Dösebacka is shown in the bar chart below (Figure 9). The result shows that the Kungälv municipality needs to upgrade the existing plant, as it is planned to, in order to prevent possible infections among the population.



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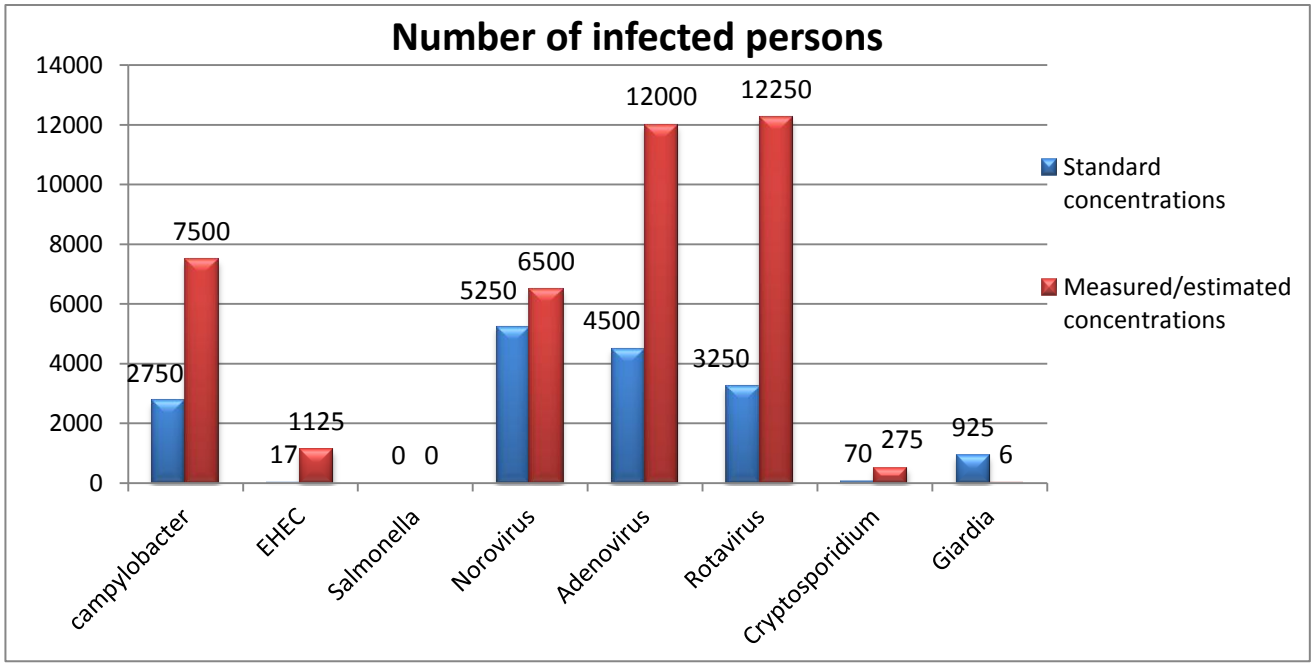


**Figure 9. The number of infected people from the current treatment plant**

## 5.2 Scenario1 (Infection risk under today's conditions)

In Scenario 1, the proposed treatment plant was checked for its efficiency in four cases (1, 2, 3 and 4) and the QMRA results for these four cases are shown below.

### 5.2.1 Case 1- Annual infection risk without chlorination

The simulated results from the QMRA model show that the annual infection risk for all pathogens does not exceed the USEPA guideline value ($<10^{-4}$) except for Adenovirus (Table 11). The annual infection risk for Adenovirus would cause an infection of 40 individuals in the city of Kungälv. In scenario zero, when the standard concentrations were used, the annual infection risk for only Adenovirus is above the USEPA guideline value and causes infection for three persons (Table 11). The daily infection risk for each pathogen considering the measured/estimated and standard concentrations is shown in detail in Appendix 2.

The pathogen removal in terms of $\log_{10}$-reduction by different barriers in the treatment system can be seen in bar chart below (Figure 10). It has been observed that the infiltration basin and UV disinfection are the most effective links regarding removal/inactivation of pathogens throughout the system. Direct filtration is more effective for removal of viruses and protozoa than for removal of bacteria. UV disinfection has less effect in inactivating Adenovirus than the other viruses. The non-effective link in the system is rapid sand filtration regarding inactivation of all pathogens but especially for bacteria. Chemical disinfection (chlorination) has no effect on inactivating of *Cryptosporidium* and is most effective in inactivating of bacteria than virus.



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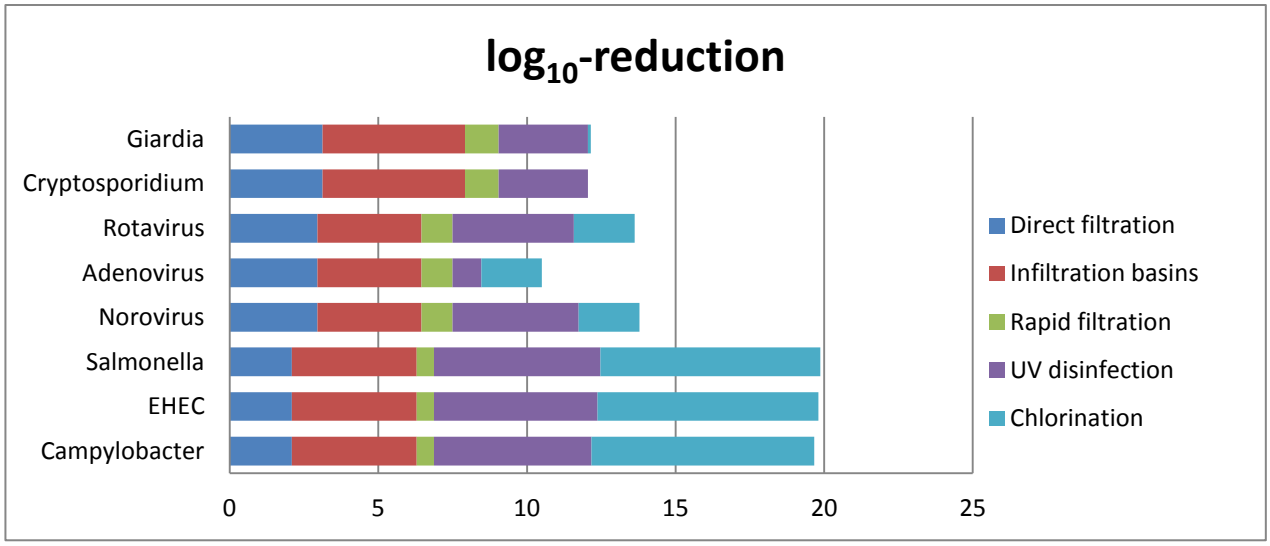


**Figure 10. $Log_{10}$–reduction by the different barriers in the proposed drinking water treatment plant**

### 5.2.2 Case 2-Annual infection risk with chlorination

In this case two alternatives were studied; the first was when the contact time for chlorine was 67 minutes, which is the time it takes for the water to reach the first consumer from the reservoir and the second is when the contact time is 127 minutes, including the retention time in the reservoir of 60 minutes and 67 minutes to reach the consumer (Appendix 2).

The results in this case show that when the proposed plant is tested with the measured/estimated concentrations (Table 11) the chemical disinfection has very significant effect on inactivation of bacteria but also inactivation of viruses especially for Adenovirus. Adenovirus failed the treatment without chlorination with $1.6\times10^{-3}$risk of infection and would affect an estimated 40 people in Kungälv. It was also observed that longer contact time with chlorine (Alternative 2) has greater impact for inactivation of viruses. The results show that chlorination has no inactivation effect on *Cryptosporidium*. The daily infection risk for all pathogens in this case is presented in Appendix 2.

The exceeded annual infection risk for Adenovirus when the proposed plant is tested with the standard concentration (scenario zero) can be reduced below the guideline value ($1.8\times10^{-5}$) if free chlorine with a dosage of 0.3 mg/l and a contact time of minimum 67 minutes considers.



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**Table 11. Annual risk of infection with and without chlorination added to the proposed treatment system**

| Pathogens | Annual infection risk for the proposed DWTP (measured & estimated concentrations) | | | Annual infection risk for the proposed DWTP (scenario zero) |
|---|---|---|---|---|
| | No Chlorination (Normal DWTP) | Chlorination[1] | Chlorination[2] | No Chlorination (Normal DWTP) |
| *Campylobacter* | 6.90E-08 | 0.00E+00 | 0.00E+00 | 7.30E-09 |
| EHEC | 1.10E-09 | 0.00E+00 | 0.00E+00 | 1.10E-11 |
| *Salmonella* | 4.50E-14 | 0.00E+00 | 0.00E+00 | 2.70E-13 |
| Norovirus | 1.80E-07 | 4.10E-09 | 3.70E-09 | 1.00E-07 |
| Adenovirus | **1.60E-03 (40)** | 5.30E-05 | 4.90E-05 | **1.30E-04 (3)** |
| Rotavirus | 2.10E-06 | 4.60E-08 | 4.20E-08 | 2.30E-07 |
| *Cryptosporidium* | 2.5E-08 | 2.50E-08 | 2.50E-08 | 1.70E-07 |
| *Giardia* | 2.5E-10 | 1.2E-10 | 1.10E-10 | 4.60E-09 |

[1]*0.4 mg/l chlorine dioxide with 67min contact time* [2]*0.4 mg/l chlorine dioxide with 127 minutes contact time*

### 5.2.3 Case 3-Annual infection risk when one barrier is removed from the treatment plant

Removal of a treatment barrier one at a time from the proposed treatment plant was considered in this case. The estimated annual infection risk for whole treatment system when one process is removed at a time is presented in Table 12. The annual risks greater than the USEPA value $1 \times 10^{-4}$ are shown with number of people likely to get infected in Kungälv in brackets. The result shows that removal of UV disinfection contributes to treatment failure for a greater number of pathogens according to the USEPA guideline value in comparison to removal of the other barriers. The system will fail for all viruses and bacteria except for *Salmonella*. After UV disinfection, the most sensitive barriers are the infiltration basins and the direct filtration respectively.

It is also important to note that the removal of rapid filtration increases the risk of infection from Adenovirus even though rapid filtration is the weakest treatment link (lower $\log_{10}$-reduction compared to the others). The number of infected people in the city of Kungälv due to an annual infection risk above the USEPA guideline value for respective pathogen is denoted by the figures in the bracket in Table 12.

**Table 12. Infection risk when a treatment barrier is removed from the system considering the measured & estimated concentrations**

| Pathogens | Annual Risk (Normal DWTP process)[1] | Annual risk of infection when a treatment process is eliminated from the system[1] | | | |
|---|---|---|---|---|---|
| | | Direct filtration | Infiltration basin | Rapid filtration | UV-disinfection |
| *Campylobacter* | 6.90E-08 | 4.00E-06 | 5.50E-05 | 2.20E-07 | **9.60E-03 (240)** |
| EHEC | 1.10E-09 | 6.40E-08 | 8.70E-07 | 3.40E-09 | **3.10E-04 (8)** |
| *Salmonella* | 4.50E-14 | 2.70E-12 | 3.70E-11 | 1.50E-13 | 1.70E-08 |
| Norovirus | 1.80E-07 | 1.70E-05 | 3.60E-05 | 9.40E-07 | **2.0E-03 (50)** |
| Adenovirus | **1.60E-03 (40)** | **8.80E-02(2 200)** | **1.3E-01(3250)** | **6.70E-03 (168)** | **8.9E-03 (223)** |
| Rotavirus | 2.10E-06 | 1.90E-04 | **4.0E-04 (10)** | 1.10E-05 | **9.7E-03 (243)** |
| *Cryptosporidium* | 2.5E-08 | 2.60E-06 | 4.90E-06 | 3.70E-07 | 1.30E-05 |
| *Giardia* | 2.5E-10 | 3.00E-08 | 2.60E-07 | 3.30E-09 | 1.6E-07 |

[1]*With measured & estimated concentrations*



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In scenario zero, according to the results in Table 13, the removal of UV disinfection causes a risk level above the USEPA guideline value for more pathogens in comparison to the removal of other barriers. The estimated daily infection risks with both the measured/estimated and the standard concentrations are presented in Appendix 2

**Table 13. Infection risk when a treatment barrier is removed from the system considering the standard concentrations**

| Pathogens | Annual Risk (Normal DWTP process)[1] | Annual risk of infection when a treatment process is eliminated from the system[1] | | | |
|---|---|---|---|---|---|
| | | Direct filtration | Infiltration basin | Rapid filtration | UV-disinfection |
| *Campylobacter* | 7.30E-09 | 4.30E-07 | 5.80E-06 | 2.30E-08 | **1.30E-03 (32)** |
| EHEC | 1.10E-11 | 6.70E-10 | 9.10E-9 | 3.60E-11 | 3.30E-6 |
| *Salmonella* | 2.70E-13 | 1,60E-11 | 2.30E-15 | 8.40E-13 | 9,70E-08 |
| Norovirus | 1.00E-07 | 9.50E-06 | 2.10E-05 | 5.40E-07 | **1.30E-03 (32)** |
| Adenovirus | **1.30E-04 (3)** | **1.10E-2 (275)** | **1.60E-2 (400)** | **6.50E-4 (16)** | **9.40E-04 (24)** |
| Rotavirus | 2.30E-07 | 1,00E-05 | 2.20E-05 | 6.30E-07 | **8.10E-04 (20)** |
| *Cryptosporidium* | 1.70E-07 | 2.70E-06 | 5.10E-05 | 6.10E-06 | **1.00E-04 (3)** |
| *Giardia* | 4.60E-09 | 4.40E-07 | 3.90E-06 | 2.70E-08 | 2.80E-06 |

[1]*With standard concentrations*

A comparison between risk levels obtained once by measured/estimated concentration and with standard concentrations results that the number of infected people due to the removal of infiltration basins and the direct filtration is higher compared to the removal of UV disinfection (Figure 11).

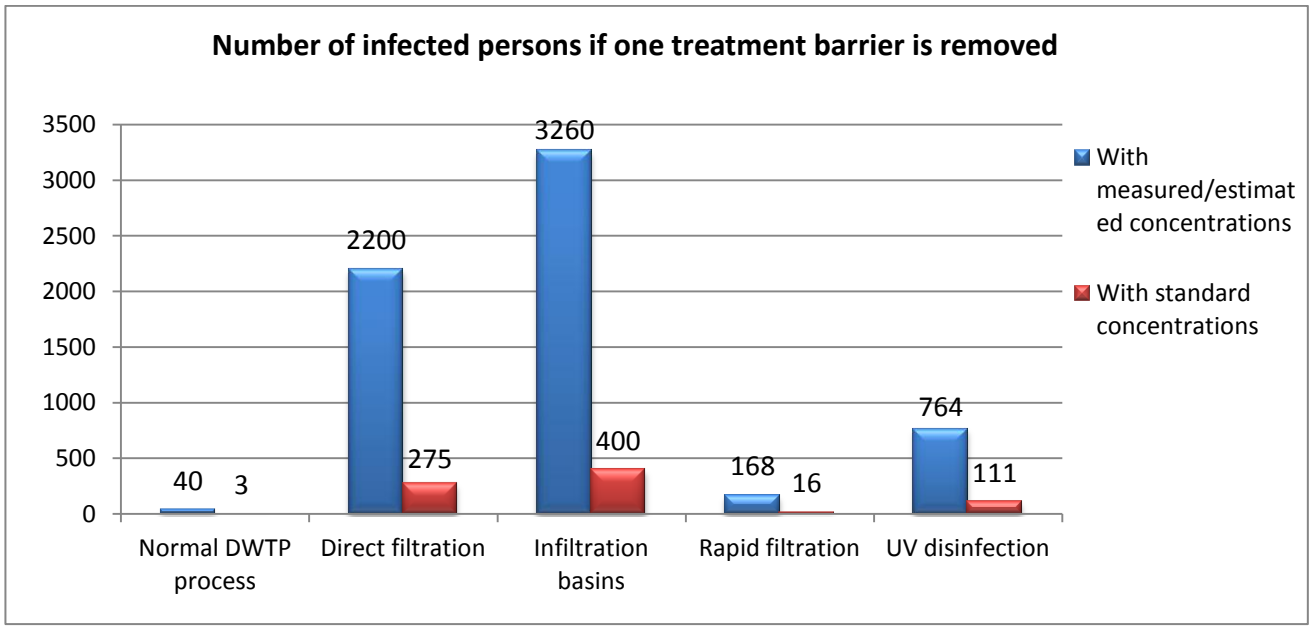


**Figure 11. Number of people infected if treatment process is removed**

### 5.2.4 Case 4-Annual infection risk with inactivation of 2 UV-units

This case considered inactivation of two UV-units during total five days in a year due to maintenance. The result shows that approximately 22 more people are likely to be affected by the Adenovirus when 2 UV-units are removed compared to when all the 4 UV-units are in operation (Table 14).

**Table 14. Annual infection risk when two UV units are out of function from the treatment system considering the measured/estimated concentrations**

| Pathogen | Annual Risk (Normal DWTP)[1] | Annual infection risk when 2 UV-units are inactivated[1] |
|---|---|---|
| *Campylobacter* | 6.90E-08 | 6.94E-08 |
| EHEC | 1.10E-09 | 1.10E-09 |
| *Salmonella* | 4.50E-14 | 4.05E-14 |
| Norovirus | 1.80E-07 | 1.80E-07 |
| Adenovirus | **1.60E-03 (40)** | **2.48E-03 (62)** |
| Rotavirus | 2.10E-06 | 2.12E-06 |
| *Cryptosporidium* | 2.50E-08 | 2.48E-08 |
| *Giardia* | 2.50E-10 | 2.48E-10 |

[1]*With measured/estimated concentrations*

If the standard concentrations consider (scenario zero) only one more person would be infected by Adenovirus compared to when all 4 UV disinfection units are operated (Table 15). The daily infection risks for both cases (with measured/estimated and standard concentrations respectively) are presented in Appendix 2.

**Table 15. Annual infection risk when two UV units are out of function from the treatment system considering the standard concentrations**

| Pathogen | Annual Risk (Normal DWTP process)[1] | Annual infection risk when 2 UV-units are inactivated[1] |
|---|---|---|
| *Campylobacter* | 7.30E-09 | 7.30E-09 |
| EHEC | 1.10E-11 | 1.13E-11 |
| *Salmonella* | 2.70E-13 | 2.84E-13 |
| Norovirus | 1.00E-07 | 1.06E-07 |
| Adenovirus | **1.30E-04 (3)** | **1.39E-04 (4)** |
| Rotavirus | 2.30E-07 | 2.26E-07 |
| *Cryptosporidium* | 1.70E-07 | 1.75E-07 |
| *Giardia* | 4.60E-09 | 4.38E-09 |

[1]*With standard concentrations*

## 5.3. Scenario 2 (Infection risk in 2060)

The estimated pathogen concentrations show an increase from 2010 to 2060 as seen in Figure 8 in section 3.4.2. The efficiency of the proposed treatment plant was studied to assess the risk it would entail if used in 2060.

### 5.3.1 Annual risk of infection for 2060

The annual infection risk for all pathogens except Adenovirus for the year 2060 does not exceed the USEPA guideline value. The simulation from QMRA model for the second scenario (2060) is presented



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in Table 16. The population of Kungälv is estimated to grow to 90 633 by year 2060. The study assumes that all the 90 633 will be connected to the DWTP making the number of people at risk of infection from Adenovirus are 13 as shown in brackets in the table. The daily infection risks are presented in Appendix 3.

### 5.3.2 Removal efficiency if the unsaturated zone in the infiltration basins changes (2060)

The study of groundwater level changes in the infiltration basins due to the climate change in the future (2060) was considered interesting to find out how the removal efficiency by infiltration basins and the annual infection risk can change if the groundwater level increases by one meter.

The increase in the groundwater level by 1 metre increases the infection risk for all pathogens (Table 16). This increase shows the importance of having a bigger unsaturated soil zone for infiltration to be effective treatment process. The result shows that the annual infection risk will exceed the guideline value for Adenovirus which would cause an infection for 16 persons in Kungälv future population.

**Table 16. Annual infection risk for the year 2060 results**

| Pathogen | Annual infection risk of proposed DWTP process today | | Annual Infection Risk in 2060 | Annual infection risk (unsaturated zone reduces by 1 metre in 2060) |
|---|---|---|---|---|
| | With measured & estimated concentration | With standard concentrations | | |
| *Campylobacter* | 6.90E-08 | 7.30E-09 | 9.30E-09 | 1.30E-08 |
| EHEC | 1.10E-09 | 1.10E-11 | 1.70E-11 | 2.40E-11 |
| *Salmonella* | 4.50E-14 | 2.70E-13 | 3.40E-13 | 4.70E-13 |
| Norovirus | 1.80E-07 | 1.00E-07 | 1.40E-07 | 1.80E-07 |
| Adenovirus | **1.60E-03 (40)** | **1.30E-04 (3)** | **1.40E-04 (13)** | **1.80E-04 (16)** |
| Rotavirus | 2.10E-06 | 2.30E-07 | 1.60E-07 | 2.00E-07 |
| *Cryptosporidium* | 2.54E-08 | 1.70E-07 | 5.10E-07 | 5.70E-07 |
| *Giardia* | 2.38E-10 | 4.60E-09 | 4.80E-09 | 5.50E-09 |

## 5.4. Scenario 3 (Infection risk if there is a waterborne disease outbreak upstream of raw water source)

Annual infection risk estimated for the third scenario when an outbreak due to the 40 % infected population from an upstream point is considered is shown in Table 17. The result shows that the proposed treatment system is capable of reducing pathogens below the USEPA guideline except for Adenovirus. The simulations were performed both with and without chlorination, and although there is a decrease in the risk of infection when there is chlorination in the treatment, the infection risk for Adenovirus is still above the guideline value. Increasing the contact time of chlorination from 67 to 127 minutes does not reduce the risk level. The daily infection risks are presented in Appendix 4.



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**Table 17. Annual infection risk in case of disease outbreak (with and without chlorination in the system)**

| Pathogens | Annual infection risk of proposed DWTP today[1] | Annual infection risk of proposed DWTP today[2] | Annual infection risk during outbreak Without Chlorination | Annual infection risk during outbreak with Chlorination[3] |
|---|---|---|---|---|
| *Campylobacter* | 6.90E-08 | 7.30E-09 | 3.18E-07 | 5.51E-08 |
| EHEC | 1.10E-09 | 1.10E-11 | 5.2E-09 | 8.70E-10 |
| *Salmonella* | 4.50E-14 | 2.70E-13 | 0.00E+00 | 3.00E-14 |
| Norovirus | 1.80E-07 | 1.00E-07 | 8.6E-07 | 1.43E-07 |
| Adenovirus | **1.60E-03(40)** | **1.30E-04 (3)** | **9.40E-03(236)** | **1.98E-03(49)** |
| Rotavirus | 2.10E-06 | 2.30E-07 | 9.9E-06 | 1.69E-06 |
| *Cryptosporidium* | 2.50E-08 | 1.70E-07 | 3.69E-06 | 3.69E-06 |
| *Giardia* | 2.50E-10 | 4.60E-09 | 2.90E-09 | 9.02E-10 |

*[1]With measured & estimated concentrations.[2]With standard concentrations.[3]0.7mg/l chlorine dioxide with 67 minutes contact time*

Increasing the number of direct filters (DynaSand) from 20 to 30 reduces the annual infection risk very slightly (Table 18) where the number of people in Kungälv at risk of infection decreases from 236 to 234. Operation of 30 sand filters together with chlorination disinfection (0.8 mg/l chlorine dioxide with 67 minutes contact time) was also studied but still forty 47 are at risk of infection compared with the 49 when operating 20 filters and chlorination (0.7mg/l chlorine dioxide with 67 minutes contact time). Increasing the number of DynaSand filter with or without chlorination reduce the number of infected persons slightly which means that increased number of filters is not effective enough to eliminate the infection risk level.

**Table 18. Annual infection risk for a disease outbreak (Adenovirus) concentration using 30 sand filters**

| | Annual infection risk | | | |
|---|---|---|---|---|
| **Pathogen** | **20 filters & without chlorination** | **30 filters & without chlorination** | **20 filters & with chlorination[1]** | **30 filters & with chlorination[2]** |
| Adenovirus | **9.40E-03(236)** | **9.34E-03(234)** | **1.98E-03(49)** | **1.89E-03(47)** |

*[1] 0.7mg/l chlorine dioxide with 67 minutes contact time. [2] 0.8 mg/l Chlorine dioxide with 67 minutes contact time*

Figure 12 below shows the annual infection risks (50 % or mean risk levels in the QMRA model) for almost all the scenarios modelled in the study against the USEPA guideline value. The USEPA value is marked with the red line. Annual risks of infection in most of the scenarios for Adenovirus are higher than the guideline value.



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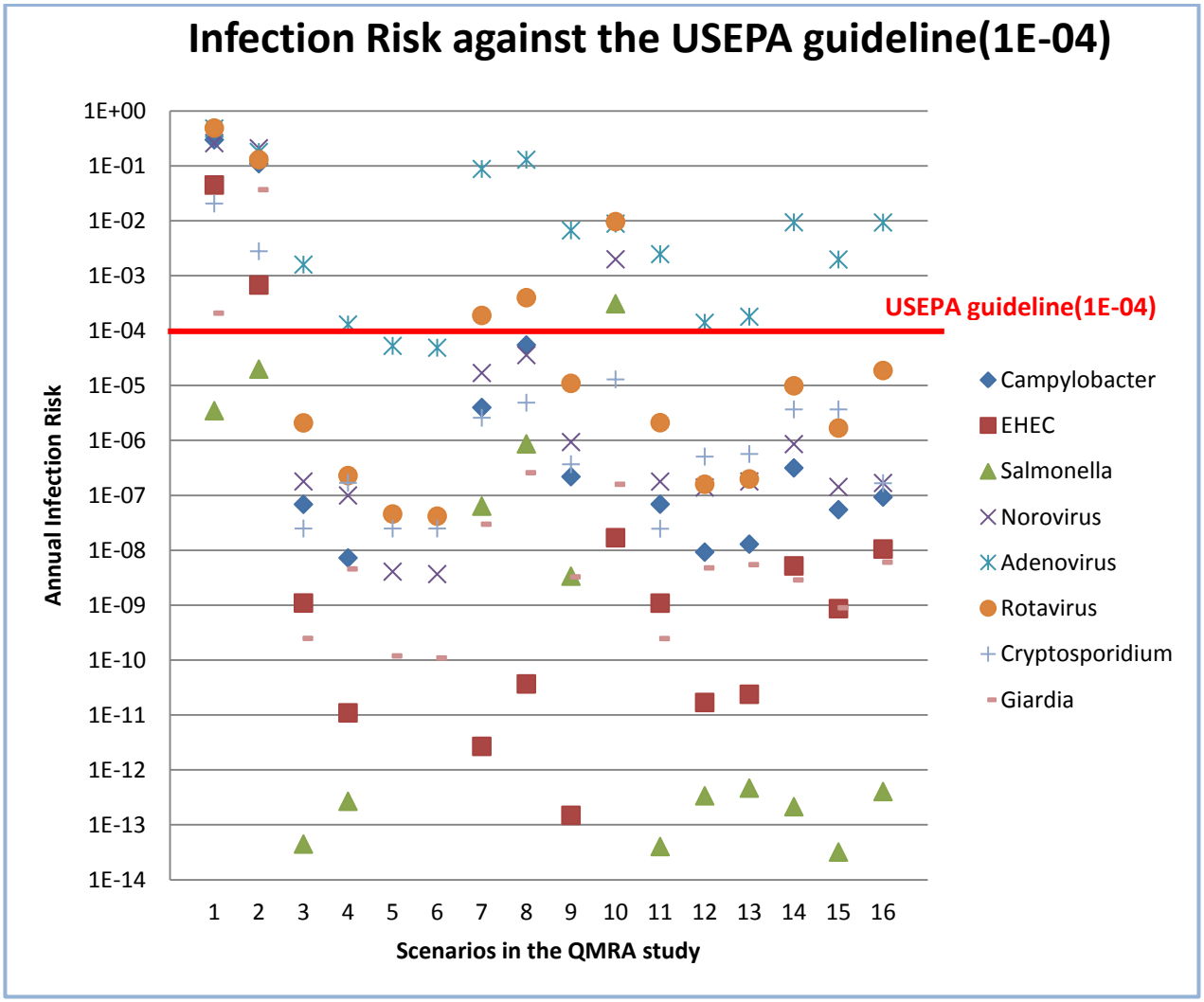


**Figure 12. Annual infection risks of the scenario cases studied against the USEPA guideline value (1 x $10^{-4}$)**

Where

| | | | |
|---|---|---|---|
| 1 - | Current DWTP with measured & estimated concentrations | | |
| 2 - | Current DWTP with Standard concentrations | | |
| 3 - | Normal DWTP with measured & estimated concentrations | Case1 | |
| 4 - | Normal DWTP with standard concentrations | Case1 | |
| 5 - | Normal DWTP – Chlorination 67 minutes | Case2 | |
| 6 - | Normal DWTP - Chlorination127 minutes | | |
| 7 - | Direct filtration removed (process failure) | | **Scenario1** |
| 8 - | Infiltration basins removed (process failure) | Case 3 | |
| 9 - | Rapid filtration removed (process failure) | | |
| 10 - | UV disinfection removed (process failure) | | |
| 11 - | 2 UV units inactivated | Case4 | |
| 12 - | 2060 (DWTP operation in the future) | | **Scenario 2** |
| 13 - | 2060 – Unsaturated zone reduces by one-meter | | |
| 14 - | Waterborne outbreak – Without chlorination | | |
| 15 - | Waterborne outbreak – With chlorination | | **Scanario3** |
| 16 - | Waterborne outbreak – with 30 DynaSand filters | | |

# 6. Discussion and recommendations

The risk analysis shows that the DWTP currently used in Kungälv is not effective in removing pathogens recorded in River Göta Älv. The annual risks of infection for all pathogens except *Salmonella* were above the USEPA guideline values and the model estimates that there is a risk that up to 12 250 residents of Kungälv will be infected with a waterborne disease from one pathogen. This high number of people infected by only one pathogen may be unrealistic due to the use of estimated concentrations by equation (2) which are higher than the standard concentrations. However, the number of infected persons when the current plant was tested with the standard concentrations is still high and this justifies the need for a new treatment plant. There has not been any waterborne disease outbreaks recorded in Kungälv which means that the risk of infection calculated in this study is higher than it actually is.

The risk analysis showed that the new proposed treatment plant is effective in removing all pathogens studied except for Adenovirus. Several cases in the three scenarios carried out for the new DWTP showed failure of Adenovirus removal although the plant was effective in removing the other pathogens. This analysis however is only microbiological and would have to be coupled with chemical and environmental analyses to conclusively confirm that the proposed treatment plant is free from risk. The chemical analysis would study the removal efficiency of chemical compounds while the environmental analysis should study site specific conditions for pathogen loading, characteristics of indicators in relation to the pathogens common for Göta Älv.

The QMRA tool estimates the significance (risk to human health) of pathogens. For this analysis; concentrations of pathogens in the Göta Älv were required as input data. The concentrations that were used were both measured and calculated, and this is likely to be a source of uncertainty in the result. Moreover most of the standard concentrations that have been considered in the study are presented by the Swedish QMRA manual as a constant concentration in River Göta älv. However the concentrations were deemed sufficiently accurate for this study and properly representative for the real world. A series of measured concentration for all studied pathogens in the Göta Älv would give a more reliable result; however, this will be too expensive and unrealistic to carry out for all pathogens.

A study of the suboptimal conditions for some barriers could have been studied in the QMRA model in order to investigate and evaluate the overall efficiency of the treatment system. However, the study of suboptimal conditions is mainly applicable to treatment barriers in the plant but does not consider the conditions outside the treatment plant. For example, in case the water pipes are cross-connected with sewer pipes, pathogen concentrations from sewer leakages that may seep into the drinking water system are difficult to quantify. Difficulty in quantifying these concentrations accurately makes the results of the annual infection risks from the QMRA model less reliable.

## 6.1 Scenario1- Proposed treatment plant with today's condition

Bacteria and virus concentrations used in the QMRA model for scenario 1 were obtained using an equation where the median concentration of indicator organism (*E.coli)* measured in the Göta älv (Lärjeholm) was considered. These measured *E.coli* concentration at Lärjeholm (located approximately 12 km downstream Kungälv) might be different from those in Kungälv due to different factors such as temperature, concentration of suspended matter and effects of the sun (ultraviolet light). This difference may cause an underestimated annual infection risk (Ferguson, et al., 2003).



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In case 1, the proposed treatment fails the USEPA guideline value for Adenovirus when no chlorination is included even when the number of direct filters is increased from 20 to 30. Therefore it is recommend include chlorination as a conventional barrier in the planned treatment plant in order to reduce the infection risk caused by Adenovirus as seen in case 2.

In case 3, treatment barriers were removed one at a time and the risk of infection by pathogens was determined with the remaining barriers in full operation within the plant. The removal of infiltration basins contributes to the highest number of persons infected by Adenovirus even though UV disinfection and direct filtration, two of the three most effective barriers remain in the treatment plant. The reason is that the highest $\log_{10}$-removal of Adenovirus is achieved by the infiltration basins and that UV disinfection is not effective for inactivation of Adenovirus (approximately 1 log).

The removal of infiltration basins was considered only as a scenario to see the efficiency and importance of this barrier. This would not happen in reality because the infiltration basins are part of the current treatment plant which will be upgraded with other processes. Furthermore, infiltration is a natural process that is not easily affected by human error like the other technical treatment processes. The removal of direct filtration which is the second most important treatment process contributes to higher number of infected persons than the removal of UV disinfection. The removal of UV causes annual risks of infection risk above USEPA guideline value for five different pathogens.

Further studies on the infiltration basins, the depth of the unsaturated zone used in the study was an average value of range from 0 m to 7.7 m obtained from the ArtDemo report (European Union, 2002). It is however not realistic to have zero metres depth of the unsaturated zone but because there are no other statistical records from Kungälv DWTP and municipality, this value was used. The probability of infiltration basins' not functioning however is minimal and the process can be relied on to function properly.

In case 4, the operation of two UV-units out of four was adjusted in the QMRA model with 2 UV-lights operating as suboptimal. This adjustment does not consider the increased inflow to the two remaining UV-units which affect low retention time for the water in the tank and consequently decrease the level of pathogens inactivation.

## 6.2 Scenario 2-Risk of infection in year 2060 for the proposed treatment system

Predictions of the future are based on estimations and modelling, and are likely to have uncertainties. The estimated annual infection risk for scenario 2 has high uncertainty due to the uncertainty in prediction of pathogen concentrations. The projected pathogens concentration and the infection risk can be used as a scenario to evaluate the efficiency of the planned treatment system in future against the anticipated increased pathogen load in the source water caused by climate change. The analysis shows that the treatment plant will efficiently remove and inactivate the pathogens in the future except for Adenovirus. So, precautionary designing is necessary even today as in the future. However, further studies of microbial risk analysis for drinking water in the future are recommended in order to attain an appropriate method for estimation of pathogen concentrations and hence an accurate result for infection risk.



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The unsaturated zones in the infiltration basins are the most effective in pathogen removal. It is important to have sufficient depth in the zones today as well as in future. Climate change in the future is expected to increase precipitation that could cause flooding in these infiltration basins. This study, as mentioned earlier estimates the level of unsaturated zone in the basins based on the ArtDemo report due to lack of recorded measurements at the municipality. Furthermore, the basins were built many years ago and using the documented results from that time might be a source of error in the result. It is recommended to further investigate the unsaturated zones of infiltration basins in Dösebacka in order to gather information that would help the analysis of their removal efficiency today as well as in the future.

### 6.3 Scenario 3- Infection risk due to an outbreak upstream of Kungälv

Estimation of bacteria and virus concentrations for this scenario follows the same procedure used for scenario 1. Therefore, there is an uncertainty of the infection risk due to the use of *E.coli* concentrations measured at Lärjeholm. Furthermore, the days one person is infected was assumed to be seven days for all pathogens even though the period of infection certainly is different for each pathogen.

The probably of a waterborne disease outbreak occurring along the Göta Älv today is small compared to international levels of waterborne disease outbreaks from river raw water sources[4]. However there have been serious outbreaks in Sweden such as the recorded one in December 2011 in Östersund, Sweden where 27 000 people suffered from cryptosporidiosis. In such a case, the proposed treatment plant will not fail in meeting the guideline value for all pathogens except for Adenovirus.

### 6.4 Recommendations

Overall, Adenovirus was the major concern for infection risk for the new planned treatment system in Kungälv for all scenarios. Adenovirus is a common source of infection to humans, mostly affecting children and immune-compromised individuals (Mena & Gerba, 2009) and occurs throughout the year (SMI, 2010). According to World Health Organisation, Adenovirus originates from human faecal matter (WHO, 2008) and into the water sources through sewage discharges. Therefore it is essential to reduce the CSOs into water sources like the Göta Älv especially considering population growth and higher precipitation in the future. One way of preventing sewer discharges is to direct the overloaded wastewater to treatment ponds and reconstruction of the wastewater network by disconnecting the stormwater from the sewage pipes, into separated sewers.

The proposed treatment plant for Kungälv is designed with UV-light as disinfection process and chlorination as an extra disinfection barrier in case of emergencies (in case of waterborne outbreaks upstream and when raw water quality exceeds recommended value of 500 CFU/100ml of *E .coli*). According to Health Canada, a study carried out by Chang et al states that Adenoviruses are much more resistant to UV disinfection compared to other enteric viruses (Health Canada, 2010). This statement has been confirmed by the high risk of infection by Adenovirus. The study showed that chlorination would reduce the annual risk of infection to a level below the USEPA guideline by effectively inactivating the Adenoviruses. Therefore, according to the results chlorination is recommended to be used in emergency situations as it is planned to be used by Norconsult.

[4] Following discussions with Thomas Pettersson (Assistant professor at Chalmers University of Technology)



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## 7. Conclusions

The drinking water consumers of the current drinking water treatment plant in Kungälv are very vulnerable to waterborne diseases due to the very high annual risks of infection. Should levels of pathogens increase in the raw water source, then the treatment plant will not effectively treat the water. It is necessary to upgrade the current treatment plant with the new proposed plant which has better pathogen removal and inactivation barriers. The study also shows that the proposed plant is not capable of removing Adenoviruses without the use of chlorination. Use of chlorination in emergency situations is recommended in this study. The study also recommends that combined sewer overflows be directed to wastewater treatment systems like treatment ponds.

This study has been a microbiological analysis and would preferably be coupled with chemical and environmental analyses to conclusively state that the proposed treatment plant is suitable for operation. Detailed studies on the pathogens in the Göta Älv would also be valuable.



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# APPENDICES

## Appendix 1

### *1-1 Drinking water guideline value in Sweden*

The drinking water quality in Sweden is categorized by the Swedish National Food Administration into two groups (suitable and unsuitable) base on the some limit values (Table 19). These limit values evaluate only the drinking water quality at the discharge point from the DWTP (effluent drinking water) and at consumers tap (Livsmedelsverkets författningssamling, 2011).

**Table 19. The Swedish limit value used to categorize water into suitable or unsuitable drinking water (Livsmedelsverkets författningssamling, 2011)**

| Microorganisms | Effluent drinking water | Drinking water at consumers tap |
|---|---|---|
| Growing microorganisms at 22 $^{o}$C | 10 number/ml | 100 number/ml |
| Slow growing bacteria | - | 5000 number/ml |
| Intestinal *enterococci* | detected in 100 ml | Detected in 100 ml |
| *Escherichia coli (E. coli*) | detected in 100 ml | Detected in 100 ml |
| Coliform bacteria | 10 number/100 ml | Detected in 100 ml |

### *1-2 Location of the Current DWTP*

Dösebacka is an Artificial Groundwater Recharge plant (AR-plant) that is situated along the western side of the Göta Älv, 5 km north of Kungälv city in Sweden (Figure13). The plant consists of one sedimentation basin, 9 infiltration basins and 15 abstraction wells (European Union, 2002).


**Figure 13. The Dösebacka infiltration basins and sedimentation basin (picture to the left (Google earth, u.d.)) and intake wells (picture to the right (Zagerholm, et al., 2007))**

### *1-3 Infiltration Basins*

Infiltration basins are a treatment process where water is percolated through a period of days to a biologically and chemically active soil environment. Infiltrated water from the basins is transported to an aquifer with both unsaturated and saturated soil conditions (Figure 14) (UNEP, 2012).

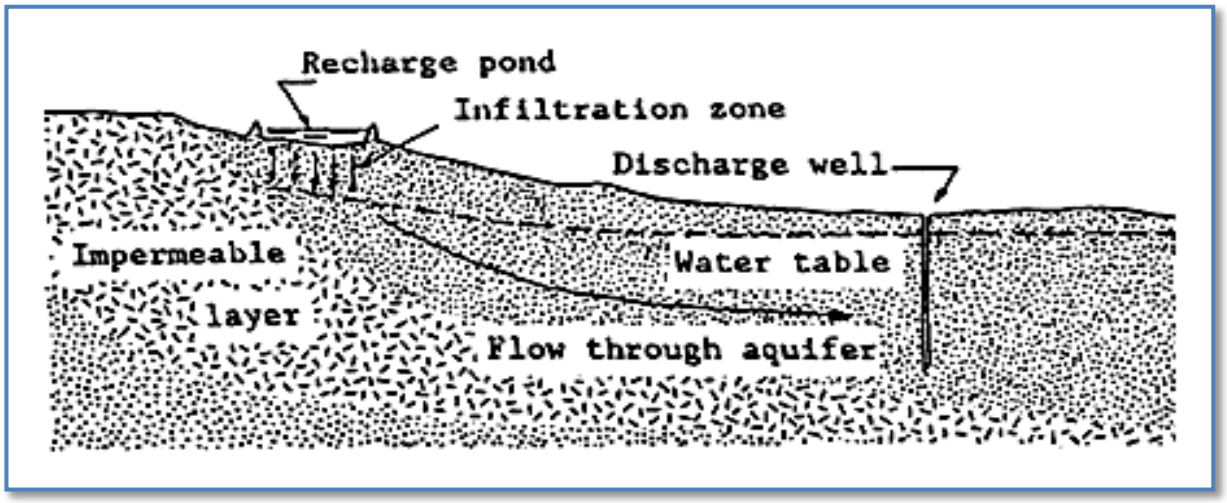


**Figure 14. Artificial Infiltration basins (UNEP, 2012)**

### *1-4 Waterborne Pathogens*

The World Health Organisation WHO has compiled a list of waterborne pathogens of interest to the water suppliers and is presented in Table 20 below (WHO, 2008).

**Table 20. Pathogens of concern to water suppliers (WHO, 2008)**

| Pathogen | Persistence in water supplies | Relative infectivity | Resistance to chlorine | Important animal source |
|---|---|---|---|---|
| **Bacteria** | | | | |
| Campylobacter spp. | Moderate | Moderate | Low | Yes |
| *E.coli*(enterohaemorrhagic) | Moderate | High | Low | Yes |
| Legionella spp. | Multiply | Moderate | Low | No |
| non-tuberculous Mycobacteria | Multiply | Low | High | No |
| Salmonella typhil paratyphi | Moderate | Low | Low | No |
| Other salmonellae | May multiply | Low | Low | Yes |
| Shigella spp | Short | Moderate | Low | No |
| Vibrio choleraeI/other vibrio | Short | Low | Low | No |
| Yersinia spp | Long | Low | Low | Yes |
| **Viruses** | | | | |
| Adenoviruses | Long | High | Moderate | No |
| Entroviruses | Long | High | Moderate | No |
| Hepatitis A virus | Long | High | Moderate | No |
| Hepatitis E virus | Long | High | Moderate | Potentially |
| Calicivirus/Noroviruses | Long | High | Moderate | No |
| Rotaviruses | Long | High | Moderate | No |
| **Parasites** | | | | |
| Entamoeba histolytica | Moderate | High | High | No |
| *Cryptosporidium spp* | Long | High | High | Yes |
| *Giardia spp* | Moderate | High | High | Yes |
| Toxoplasma gondii | Long | High | High | Yes |



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### *1-5 Viruses*

More than 100 different types of enteric viruses have been identified in human faeces and the major groups of enteric virus that have been examined in the raw sewage or come from both infected and healthy individuals (Table 21) (Joseph, et al., 1978).

**Table 21. Different viruses identified in faeces of healthy and infected humans found in the raw sewage (Joseph, et al., 1978)**

| Virus Group | Number of types | Disease or sign caused |
|---|---|---|
| Poliovirus | 3 | Paralysis, Meningitis, fever |
| Echovirus | 34 | Meningitis, respiratory disease, rash, diarrhoea, fever |
| Coxsackievirus A | 24 | Meningitis, respiratory disease, herpangina, fever |
| Coxsackievirus B | 6 | Myocarditis, congenital heart anomalies, Meningitis, respiratory disease, rash, pleurodynia, fever |
| New enteroviruses | 4 | Meningitis, respiratory disease, encephalitis, acute haemorrhagic conjunctivitis, fever |
| Hepatitis A (probably enterovirus) | 1 | Infectious hepatitis |
| Gastroenteritis A (probably an enterovirus) | 2 | Epidemic vomiting and diarrhoea, fever |
| Rotavirus (reovirus family)(gastroenteritis type B) | 3 | Epidemic vomiting and diarrhoea, chiefly of children |
| Reovirus | 3 | not clearly established |
| Adenovirus | >30 | Respiratory disease, eye infections |
| Parvovirus (Adeno-associated virus) | 3 | Associated with respiratory disease of children, but etiology not clearly established |

### *1-6 Triangular distribution*

If the data contains the most likely estimate in addition to the minimum and the maximum estimates, then the triangular distribution is the appropriate probability distribution used to describe the data variety within the most likely value. This probability is constructed by placing the most likely value, referred to as the mode, at the point of the triangle. The shape of the triangle might be skewed to the left (minimum) or right (maximum) values depending on minimum, maximum and mode estimates (Figure 15). Triangular distribution benefits users in a way that is simple to calculate and generate but it has limited ability to model the real world estimates (RiskAMP, 2011).



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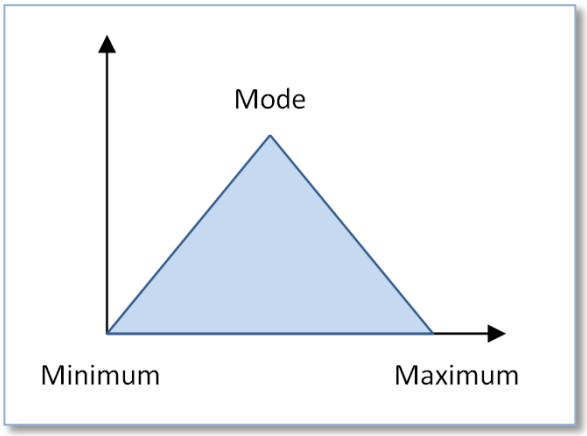


**Figure 15. Triangular probability distribution (minimum, mode, maximum)**

In the QMRA model, the removal efficiency (log10-reduction) for each treatment process was put as triangular distribution and Table 3 shows the input value for each barrier.

*Removal efficiency of infiltration basins (current treatment plant)*

The removal efficiency for the infiltrations basins in Dösebacka treatment plant was measured to 3 $log_{10}$-reduction with 99.9% removal efficiency (European Union, 2002); however, in the QMRA model the removal efficiency was preferred as triangular distribution. At Dösebacka AR-plant, the only measured removal efficiency was for bacteria and not for viruses and protozoa (European Union, 2002). It was therefore preferable to use the removal efficiency of slow sand filtration for all the pathogens in order to obtain a uniform estimation for all (Table22).

**Table 22. Removal efficiency ($log_{10}$-reduction) in slow sand filtration for pathogens**

| Pathogen | Bacteria [a] | Virus [a] | Protozoa [a] | |
|---|---|---|---|---|
| | | | ***Cryptosporidium*** | ***Giardia*** |
| **Minimum** | 1.2 | 0.6 | 0.3 | 1.2 |
| **Likeliest** | 2.7 | 2.2 | 3.8 | 3.3 |
| **Maximum** | 4.8 | 4.0 | 6.5 | 6 |

[a] (Smeets, et al., 2006)

The study approximates 0.5$log_{10}$-reduction per meter of unsaturated zone in the infiltration layers (Forss[5], 2012); therefore the total pathogen removal by infiltration basins can be estimated by equation (8).

$$Total\ removal\ efficiency = (log_{10}\ reduction)_{SSF} + 0.5 log_{10} reduction\ /unsaturated\ zone \qquad (8)$$

The modification by the equation was applied to the likeliest and maximum removal efficiencies of the slow sand filters to obtain removal efficiency for infiltration. The minimum removal efficiency was not modified and the infiltration basins were assumed to have the same value as the slow sand filters. The unsaturated zone in Dösebacka varies from zero to 7.7 meters for the infiltration basins (European Union, 2002) therefore the average depth of the zone (3.85 metre) has been assumed for the equation (8) and the total removal efficiency is then presented in Table 23.

[5]The values were decided upon during a discussion at Norconsult with Madeleine Forss.



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**Table 23. Estimated removal efficiency for the infiltration basins in Kungälv AR-plant**

| Pathogen | Bacteria | Virus | Protozoa | |
|---|---|---|---|---|
| | | | *Cryptosporidium* | *Giardia* |
| **Minimum** | 1.2 | 0.6 | 0.3 | 1.2 |
| **Likeliest** | 4.6 | 4 | 5.7 | 5 |
| **Maximum** | 6.7 | 6 | 8.4 | 8 |

### *1-7 Current DWTP*

Table 24 below shows the daily and annual infection risks for the DWTP used currently. The number of infected persons is in the bracket.

**Table 24. Daily and annual risk of the DWTP currently used**

| Pathogen | Daily infection risk[1] | Annual infection risk[1] | Daily infection risk[2] | Annual infection risk[2] |
|---|---|---|---|---|
| *Campylobacter* | 5.10E-03 | **3.0E-01 (7 500)** | 7.50E-04 | **1.10E-01 (2 750)** |
| EHEC | 1.80E-04 | **4.5E-02 (1 125)** | 1.90E-06 | **6.80E-04 (17)** |
| *Salmonella* | 9.60E-09 | 3.5E-06 | 5.50E-08 | 2.0E-05 |
| Norovirus | 4.10E-03 | **2.60E-01 (6 500)** | 2.50E-03 | **2.10E-01 (5250)** |
| Adenovirus | 2.60E-02 | **4.80E-01 (12 000)** | 1.80E-03 | **1.80E-01 (4 500)** |
| Rotavirus | 2.50E-02 | **4.90E-01 (12 250)** | 1.8E-03 | **1.30E-01 (3 250)** |
| *Cryptosporidium* | 5.30E-05 | **1.10E-02 (275)** | 8.0E-06 | **2.80E-03 (70)** |
| *Giardia* | 5.90E-07 | **2.20E-04 (6)** | 5.10E-04 | **3.70E-02 (925)** |

[1]*With measured/estimated concentrations.* [2]*With standard concentrations*



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# Appendix 2: Scenario1 (year 2011)

***2-1 Gamma distribution***

The gamma distribution models sums of exponentially distributed random variables and is a family of curves described by two parameters, shape (ρ) and scale (λ)(Figure 16). The Gamma distribution is flexible for describing the probability density functions (PDFs) of different shapes. When ρ is large, the gamma distribution closely approximates a normal distribution with the advantage that the gamma distribution has density only for positive real numbers (MathWorks, 2012). The equation of gamma distribution is shown below;

Gamma distribution: $g(\mu/\rho,\lambda) = \frac{\lambda^{\rho}}{\Gamma(\rho)}\,\mu^{\rho-1}e^{-\lambda\mu}$ (9)

Where $\mu = mean\ number\ of\ microorganisms\ per\ litre.\ \rho = \text{Shape},\ \text{and}\ \lambda = \text{scale}$

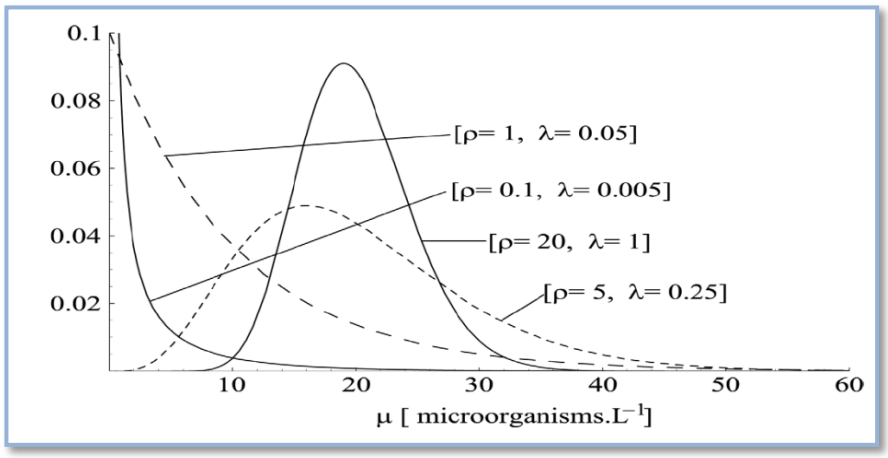


**Figure 16. Gamma probability distribution (MathWorks, 2012)**

The shape and scale of a gamma distribution can be estimated from the mean and variance for the gamma distribution which are expressed as below (Råde, o.a., 2005):

$$Mean = Scale * Shape \quad (10)$$

$$Variance = Scale^2 * Shape \quad (11)$$

Then the formula for obtaining the shape and scale for the continuous data can be written as below:

$$Shape = \left({Mean}/{stdev}\right)^2 \quad (12)$$

$$Scale = {Stdev^2}/{Mean} \quad (13)$$

***2-2 lognormal distribution***

Lognormal distribution is used for a number of independent variables with positive values. Also it refers to the probability distribution of a variable with a normally distributed logarithm. In the QMRA model, when the standard concentrations are used, pathogens with the constant concentration are expressed with a median value equal to the constant concentration and a standard deviation equal to one. Otherwise, the mean and standard deviation are same as it is given in the Swedish QMRA model (Lundberg Abrahamsson, et al., 2009).



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### *2-3 Pathogen Concentrations calculations*

*Virus and bacteria concentration*

The measured concentrations for bacteria and virus based on equation (2) are shown in Table 25.

**Table 25. Calculated bacteria and virus concentrations in Göta älv**

| Year | Measured Median concentration of *E.coli* in Göta Älv (CFU/litre) | Calculated concentrations of Bacteria and Viruses ($P_d = p.\frac{P_f}{I_f}.I_d$) (Number/litre) with a 0.2% risk level) | | | | |
|---|---|---|---|---|---|---|
| | | Bacteria | | | Virus | |
| | | EHEC | *Campylobacter* | *Salmonella* | Adenovirus/ Rotavirus | Norovirus |
| 2002 | 900 | 9.90 | 9.90 | 0.18 | 18.0 | 1.80 |
| 2003 | 860 | 9.46 | 9.46 | 0.172 | 17.2 | 1.72 |
| 2004 | 980 | 10.78 | 10.78 | 0.196 | 19.6 | 1.96 |
| 2005 | 740 | 8.14 | 8.14 | 0.148 | 14.8 | 1.48 |
| $P_f$ | | 5.50E+07 | 5.50E+07 | 1.00E+06 | 1.00E+08 | 1.00E+07 |
| $I_f$ | | 1.00E+07 | 1.00E+07 | 1.00E+07 | 1.00E+07 | 1.00E+07 |
| $p$ | | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| **Average** | | 9.57 | 9.57 | 0.17 | 17.40 | 1.74 |
| **STDEV** | | 1.10 | 1.10 | 0.02 | 2.00 | 0.20 |
| **Shape** | | 75.69 | 75.69 | 75.69 | 75.69 | 75.69 |
| **Scale** | | 0.13 | 0.13 | 0.0023 | 0.23 | 0.023 |

*Cryptosporidium and Giardia concentration*

Measured concentration of *Cryptosporidium* and *Giardia* in Göta Älv (Bergstedt, 2012), together with the calculated gamma parameters (shape and scale) for protozoa (Table 26)

**Table 26. Measured Cryptosporidium and Giardia in Göta älv ( (Bergstedt, 2012)**

| Year | Measured concentrations in Göta Älv (Number/litre) | |
|---|---|---|
| | *Cryptosporidium* | *Giardia* |
| **2005** | 0.08, 0.08. 0.1, 0.1,0.1,0.07,0.1 | 0.08, 0.08. 0.1, 0.1,0.1,0.07,0.1 |
| **2006** | 0, 0.1, 0, 0, 0,0 | 0, 0.1, 0, 0, 0,0 |
| **2007** | 0, 0, 0, 0, 0, 0, 0,0,0,0.2 | 0, 0, 0, 0, 0, 0, 0.2,0.1,0,0 |
| **2008** | 0, 0, 0, 0,0,0,0,0 | 0, 0, 0, 0,0,0,0,0 |
| **2009** | 0, 0, 0, 0, 0,0.1,0 | 0, 0, 0, 0, 0,0,0 |
| **2010** | 0, 0, 0, 0.2,0 | 0, 0, 0, 0.2,0 |
| **2011** | 0.1, 0.1, 0.013, 0.1, 0.1, 0.1,0.1 | 0.1, 0.1, 0.013, 0.1, 0.1, 0.1,0.1 |
| **Average** | 0.04 | 0.04 |
| **STDEV** | 0.06 | 0.06 |
| **Shape** | 0.44 | 0.46 |
| **Scale** | 0.08 | 0.08 |



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***2-4 MRA result***

The results from the first scenario and its four cases are presented in Tables below.

### *2-4.1 Case 1-Annual infection risk without chlorination*

Table 27 shows the $Log_{10}$-reduction of the proposed treatment processes excluding chlorination. It also includes the daily and annual infection risks when measured/estimated concentrations were used. The daily and annual infection risks when the standard concentrations were considered in the QMRA model is shown in Table 28.

**Table 27. $Log_{10}$- reduction and infection risk without chlorination (with measured and standard concentrations)**

| Pathogens | $Log_{10}$- reduction | | | | Daily infection risk | Annual risk of infection |
|---|---|---|---|---|---|---|
| | Direct Filtration | Infiltration basins | Rapid Filtration | UV Disinfection | | |
| *Campylobacter* | 2.09 | 4.2 | 0.58 | 5.3 | 1.90E-10 | 6.90E-08 |
| EHEC | 2.09 | 4.2 | 0.58 | 5.5 | 3.0E-12 | 1.10E-09 |
| *Salmonella* | 2.09 | 4.2 | 0.58 | 5.6 | 1.20E-16 | 4.50E-14 |
| Norovirus | 2.95 | 3.5 | 1.05 | 4.24 | 4.90E-10 | 1.80E-07 |
| Adenovirus | 2.95 | 3.5 | 1.05 | 0.959 | 6.80E-06 | **1.60E-03 (40)** |
| Rotavirus | 2.95 | 3.5 | 1.05 | 4.08 | 5.80E-09 | 2.10E-06 |
| *Cryptosporidium* | 3.12 | 4.8 | 1.13 | 3 | 6.80E-11 | 2.50E-08 |
| *Giardia* | 3.12 | 4.8 | 1.13 | 3 | 6.80E-13 | 2.50E-10 |
| **Sum** | **21.36** | **32.7** | **7.15** | **31.679** | | |

**Table 28. Daily and annual infection risk with standard concentrations**

| Pathogen | Daily infection risk | Annual risk of infection |
|---|---|---|
| *Campylobacter* | 2.00E-11 | 7.30E-09 |
| EHEC | 3.10E-14 | 1.10E-11 |
| *Salmonella* | 7.30E-16 | 2.70E-13 |
| Norovirus | 2.90E-10 | 1.00E-07 |
| Adenovirus | 3.80E-07 | **1.30E-04 (3)** |
| Rotavirus | 6.20E-10 | 2.30E-07 |
| *Cryptosporidium* | 4.80E-10 | 1.70E-07 |
| *Giardia* | 1.20E-11 | 4.60E-09 |

### *2-4.2 Case 2-Annual infection risk with chlorination*

#### *Calculation of chlorine contact time in the reservoirs*

The design of the new reservoirs in the proposed treatment plant is schematically presented in Figure 17. The total volume for the two reservoirs is equal to 5000 $m^3$/day.



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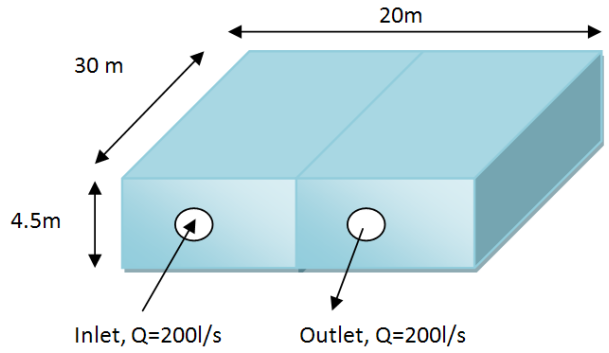


**Figure 17. Schematic figure of reservoirs and the direction of the inlet and out let flows**

Average velocity in the reservoir is equal to: $V = \frac{Q}{A} = \frac{0.2m^3/s}{(4.5*10)} = 0.004m/s$

The retention time in the reservoir is equal to: $t = \frac{s}{v} = \frac{40m}{0.004m/s} = 9000\ seconds\ or\ 2.5\ hour$

It is assumed that the average velocity is 3 times greater than the minimum velocity. Then the minimum retention time is 3 times lower than the average retention time which is equal to: $t = \frac{2.5\ h}{3} = 1\ hour$

Retention time in distribution network

The total flow from two tanks to the consumers in Kungälv is 100l/s. Thereafter by using Colebrook diagram the dimension of pipe can roughly be estimated.

$$\left.\begin{array}{l} Q = 100\ l/s\ or\ 0.1m^3/s \\ Friction\ slope\ is\ 5‰ \end{array}\right\} \quad The\ pipe\ diameter\ is\ approximately\ 320mm\ or\ 0.32m$$

The pipe area is $A = \pi.r^2 = \pi.(\frac{0.32}{2})^2 = 0.08m^2$

Velocity in the pipe network is $v = \frac{Q}{A} = \frac{0.1m^3/s}{0.08m^2} = 1.25m/S$

It is stated that the Dösebacka AR-plant is located approximately 5 km from the north of the Kungälv. Then the retention time in the distribution network from the reservoirs to the first consumers that have been assumed to be 5 km far away from the plant is equal to:

$$t = \frac{s}{v} = \frac{5000m}{1.25m/s} = 4000\ s\ or\ 67min$$



`

*MRA Results*

Table 29 shows daily and annual risks of infection when chlorination is added to the system at different contact times

**Table 29. Daily infection risks with chlorination**

| Pathogens | Daily risk of infection[1] | | |
|---|---|---|---|
| | No chlorination | Chlorination[2] | Chlorination[3] |
| *Campylobacter* | 1.90E-10 | 0.00E+00 | 0.00E+00 |
| EHEC | 3.0E-12 | 0.00E+00 | 0.00E+00 |
| *Salmonella* | 1.20E-16 | 0.00E+00 | 0.00E+00 |
| Norovirus | 4.90E-10 | 4.10e-09 | 1.00E-11 |
| Adenovirus | 6.80E-06 | 1.50E-07 | 1.40E-07 |
| Rotavirus | 5.80E-09 | 1.30E-10 | 1.10E-10 |
| *Cryptosporidium* | 6.80E-11 | 6.80E-11 | 6.80E-11 |
| *Giardia* | 6.80E-13 | 3.20E-13 | 3.10E-13 |

*[1] With measured/estimated concentrations. [2]0.4mg/l chlorine dioxide with 67minutes contact time. [3]0.4mg/l chlorine dioxide with 127 minutes contact time*

*2-4.3 Case 3-Removal of one barrier from the treatment system*

Table 30 shows the daily probability of infection when a treatment barrier is closed down. It is from these risks that the annual risks of infection for protozoa are calculated in Table 13.These risk values were obtained from the measured and estimated concentration of pathogens.

**Table 30. Daily infection risk when a barrier is closed down considering the measured/estimated concentrations**

| Pathogens | Daily Infection risk[1] | | | |
|---|---|---|---|---|
| | Direct filtration | Infiltration Basins | Rapid Filtration | UV-light Disinfection |
| *Campylobacter* | 1.10E-08 | 1.50E-07 | 6.0E-10 | 3.40E-05 |
| EHEC | 1.70E-10 | 2.40E-9 | 9.40E-12 | 8.60E-07 |
| *Salmonella* | 7.40E-15 | 1.00E-13 | 4.0E-16 | 4.60E-11 |
| Norovirus | 4.50E-08 | 9.80E-08 | 2.60E-09 | 7.40E-06 |
| Adenovirus | 6.00E-04 | 1.20E-03 | 3.40E-05 | 5.10E-05 |
| Rotavirus | 5.10E-07 | 1.10E-06 | 2.90E-08 | 6.00E-05 |
| *Cryptosporidium* | 7.20E-09 | 1.30E-08 | 1.00E-09 | 3.50E-08 |
| *Giardia* | 8.30E-11 | 7.10E-10 | 9.00E-12 | 4.40E-10 |

*[1]With measured/estimated concentrations*

The daily infection risks when the standard concentrations are used in the QMRA model are shown in Table 31.



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**Table 31. Daily infection risk when a barrier is closed down considering standard concentrations**

| Pathogens | Daily Infection risk[1] | | | |
|---|---|---|---|---|
| | Direct filtration | Infiltration Basins | Rapid Filtration | UV-light Disinfection |
| *Campylobacter* | 1.20E-09 | 1.60E-08 | 6.30E-11 | 3.60E-06 |
| EHEC | 1.80E-12 | 2.50E-11 | 9.90E-14 | 9.10E-09 |
| *Salmonella* | 4.30E-14 | 5.80E-13 | 2.30E-15 | 2.70E-10 |
| Norovirus | 2.60E-08 | 5.70E-08 | 1.50E-09 | 4.30E-06 |
| Adenovirus | 3.50E-05 | 7.50E-05 | 2.0E-06 | 3.0E-06 |
| Rotavirus | 2.90E-08 | 6.10E-08 | 1.70E-09 | 3.10E-06 |
| *Cryptosporidium* | 7.50E-08 | 1.40E-07 | 1.80E-08 | 3.0E-07 |
| *Giardia* | 1.20E-09 | 1.10E-08 | 7.50E-11 | 7.80E-09 |

[1]*With standard concentrations*

### *2-4.4 Case 4-Inactivation of 2 UV disinfection units*

Daily- and annual risks of infection caused by inactivation of 2 UV-disinfection units from the treatment during maintenance considered to take in total five days during year is shown in Table 32.

**Table 32. Infection risk when 2 UV units are functional considering measured/estimated concentrations**

| Pathogen | Inactivation of 2 UV-units[1] | |
|---|---|---|
| | Daily infection risk | Annual risk of infection |
| *Campylobacter* | 1.90E-10 | 6.94E-08 |
| EHEC | 3.0E-12 | 1.10E-09 |
| *Salmonella* | 1.20E-16 | 4.05E-14 |
| Norovirus | 5.10E-10 | 1.79E-07 |
| Adenovirus | 6.80E-06 | **2.48E-03 (62)** |
| Rotavirus | 5.80E-09 | 2.12E-06 |
| *Cryptosporidium* | 6.80E-11 | 2.48E-08 |
| *Giardia* | 6.80E-13 | 2.48E-10 |

[1]*With measured and estimated concentrations*

The table below shows the result of annual infections risks when standard concentrations were used.

**Table 33. Infection risk when 2 UV units are functional considering standard concentrations**

| Pathogen | Inactivation of 2 UV-units[1] | |
|---|---|---|
| | Daily infection risk | Annual risk of infection |
| *Campylobacter* | 2.00E-11 | 7.30E-09 |
| EHEC | 3.10E-14 | 1.13E-11 |
| *Salmonella* | 7.30E-16 | 2.84E-13 |
| Norovirus | 2.90E-10 | 1.06E-07 |
| Adenovirus | 3.80E-07 | **1.39E-04** |
| Rotavirus | 6.20E-10 | 2.26E-07 |
| *Cryptosporidium* | 4.80E-10 | 1.75E-07 |
| *Giardia* | 1.20E-11 | 4.38E-09 |

[1]*With standard concentrations*

# Appendix 3: Scenario 2 (year 2060)

***3-1 Extreme pathogen concentration 2060***

The exponential equation used to predict the pathogens concentration from year 2010 until year 2060 is shown below. Furthermore in Table 34, the estimated concentration based on the below equation and the gamma distribution parameters used in the MRA model are presented in more detail.

$$C = C_p . 1.01^x \quad (6)$$

$x = Is\ the\ number\ of\ years\ from\ year\ 2010\ to\ year\ 2060$

$C = Pathogen\ in\ source\ water$

$C_p = Pathogens\ in\ source\ water$ in 2010

**Table 34. Estimated pathogens concentrations from year 2010 to 2060**

| Year | Estimated pathogen concentrations for 2060 with 1% increase every year from 2010 to 2060 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **EHEC** | ***Salmonella*** | ***Campylobacter*** | **Norovirus** | **Adenovirus** | **Rotavirus** | ***Cryptosporidium*** | ***Giardia*** |
| 2010 | 0.1 | 1 | 1 | 1 | 1 | 1 | 0.4 | 0.5 |
| 2015 | 0.11 | 1.05 | 1.05 | 1.05 | 1.05 | 1.05 | 0.42 | 0.53 |
| 2020 | 0.11 | 1.10 | 1.10 | 1.10 | 1.10 | 1.10 | 0.44 | 0.55 |
| 2025 | 0.12 | 1.16 | 1.16 | 1.16 | 1.16 | 1.16 | 0.46 | 0.58 |
| 2030 | 0.12 | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 | 0.49 | 0.61 |
| 2035 | 0.13 | 1.28 | 1.28 | 1.28 | 1.28 | 1.28 | 0.51 | 0.64 |
| 2040 | 0.13 | 1.35 | 1.35 | 1.35 | 1.35 | 1.35 | 0.54 | 0.67 |
| 2045 | 0.14 | 1.42 | 1.42 | 1.42 | 1.42 | 1.42 | 0.57 | 0.71 |
| 2050 | 0.15 | 1.49 | 1.49 | 1.49 | 1.49 | 1.49 | 0.60 | 0.74 |
| 2055 | 0.16 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 | 0.63 | 0.78 |
| 2060 | 0.16 | 1.64 | 1.64 | 1.64 | 1.64 | 1.64 | 0.66 | 0.82 |
| **Average** | **0.13** | **1.30** | **1.30** | **1.30** | **1.30** | **1.30** | **0.52** | **0.65** |
| **STDEV** | 0.02 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 | 0.09 | 0.11 |
| **Shape** | 37 | 37 | 37 | 37 | 37 | 37 | 37 | 37 |
| **Scale** | 0.004 | 0.035 | 0.035 | 0.035 | 0.035 | 0.035 | 0.014 | 0.018 |

***3-2 Daily and Annual infection in 2060***

Both daily-and annual infection for year 2060 estimated with measured/estimated and standard concentrations are shown in table below.



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**Table 35. Daily and annual infection risk for year 2060**

| Pathogen | Scenario 2-2060 | | | |
|---|---|---|---|---|
| | Daily risk in 2060[1] | Annual Infection Risk in 2060[1] | Daily risk in 2060[2] | Annual Infection Risk in 2060[2] |
| *Campylobacter* | 5.50E-09 | 1.65E-07 | 2.50E-11 | 9.30E-09 |
| EHEC | 7.90E-11 | 2.46E-09 | 4.80E-14 | 1.70E-11 |
| *Salmonella* | 4.50E-15 | 1.20E-13 | 9.30E-16 | 3.40E-13 |
| Norovirus | 1.50E-08 | 4.40E-07 | 3.90E-10 | 1.40E-07 |
| Adenovirus | 1.80E-04 | **5.58E-03 (506)** | 4.40E-07 | **1.40E-04 (13)** |
| Rotavirus | 1.70E-07 | 5.07E-06 | 4.30E-10 | 1.60E-07 |
| *Cryptosporidium* | 7.60E-08 | 1.39E-06 | 1.40E-09 | 5.10E-07 |
| *Giardia* | 5.60E-11 | 1.24E-09 | 1.30E-11 | 4.80E-09 |

[1]*With measured and estimated concentrations.*[2]*With standard concentrations*

Table below shows the daily and annual infection risks with both measured/estimated and standard concentrations when a one-metre rise of groundwater table in 2060 is considered.

**Table 36. Daily and annual infection risk for year 2060 in case of raised groundwater table by one-metre**

| Pathogen | Scenario2 – 2060 (rise of groundwater table by one-metre) | | | |
|---|---|---|---|---|
| | Daily risk in 2060[1] | Annual Infection Risk in 2060[1] | Daily risk in 2060[2] | Annual Infection Risk in 2060[2] |
| *Campylobacter* | 7.50E-09 | 5.08E-07 | 3.50E-11 | 1.30E-08 |
| EHEC | 1.20E-10 | 8.12E-09 | 6.50E-14 | 2.40E-11 |
| *Salmonella* | 6.40E-15 | 4.20E-13 | 1.30E-15 | 4.70E-13 |
| Norovirus | 1.90E-08 | 1.29E-06 | 5.00E-10 | 1.80E-07 |
| Adenovirus | 1.90E-04 | **1.34E-02 (1 213)** | 5.40E-07 | **1.80E-04 (16)** |
| Rotavirus | 2.00E-07 | 1.38E-05 | 5.60E-10 | 2.00E-07 |
| *Cryptosporidium* | 8.40E-08 | 5.06E-06 | 1.60E-09 | 5.70E-07 |
| *Giardia* | 6.40E-11 | 4.06E-09 | 1.50E-11 | 5.50E-09 |

[1]*With measured and estimated concentrations.*[2]*With standard concentrations*

# Appendix 4: Scenario 3-Waterborn outbreak upstream of Kungälv

### *4-1 MRA Input Data*

Table 37 shows the calculated concentration of pathogens due to an outbreak of pathogens caused by a 40 % infected population upstream the city of Kungälv remaining for two and half months. The concentrations are obtained using equation (2) and the measured median concentration of *E.coli* in Göta Älv (CFU/l).

**Table 37. Concentrations of pathogens due to an outbreak upstream the city of Kungälv**

| Year | Calculated concentrations per litre at a 40% risk of infection for 2.5 months | | | | | | |
|---|---|---|---|---|---|---|---|
| | Virus | | Bacteria | | | Protozoa | |
| | Adenovirus / Rotavirus | Norovirus | EHEC | *Campylobacter* | *Salmonella* | *Cryptosporidium* | *Giardia* |
| **2002** | 336.00 | 33.60 | 184.80 | 184.80 | 3.36 | 18.48 | 1.85 |
| **2003** | 321.07 | 32.11 | 176.59 | 176.59 | 3.21 | 17.66 | 1.77 |
| **2004** | 365.87 | 36.59 | 201.23 | 201.23 | 3.66 | 20.12 | 2.01 |
| **2005** | 276.27 | 27.63 | 151.95 | 151.95 | 2.76 | 15.19 | 1.52 |
| $P_f$ | 1.00E+08 | 1.00E+07 | 5.50E+07 | 5.50E+07 | 1.00E+06 | 5.50E+06 | 5.50E+05 |
| $I_f$ | 1.00E+07 | 1.00E+07 | 1.00E+07 | 1.00E+07 | 1.00E+07 | 1.00E+07 | 1.00E+07 |
| $p$ | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| **Average** | 324.80 | 32.48 | 178.64 | 178.64 | 3.25 | 17.86 | 1.79 |
| **STDEV** | 37.33 | 3.73 | 20.53 | 20.53 | 0.37 | 2.05 | 0.21 |
| **Shape** | 75.69 | 75.69 | 75.69 | 75.69 | 75.69 | 75.69 | 75.69 |
| **Scale** | 4.29 | 0.429 | 2.36 | 2.36 | 0.043 | 0.24 | 0.024 |

### *4-2 QMRA Results*

Table 38 shows the daily and annual infection risks during an outbreak when there is no chlorination use in the treatment system.

**Table 38. Infection risks during an outbreak and there is no chlorination**

| Pathogens | Daily infection risk during outbreak (No chlorination) | Annual infection risk during an outbreak (No chlorination) |
|---|---|---|
| *Campylobacter* | 3.50E-09 | 3.18E-07 |
| EHEC | 5.80E-11 | 5.2E-09 |
| *Salmonella* | 2.40E-15 | 0.00E+00 |
| Norovirus | 9.60E-09 | 8.6E-07 |
| Adenovirus | 1.00E-04 | **9.40E-03(236)** |
| Rotavirus | 1.10E-07 | 9.9E-06 |
| *Cryptosporidium* | 4.90E-08 | 3.69E-06 |
| *Giardia* | 3.60E-11 | 2.90E-09 |



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Table 39 shows the daily and annual infection risks during an outbreak and when chlorination with chlorine dioxide and a dosage of 0.7 mg/l (alternative 1) is used in the treatment system. The table also shows the $log_{10}$- reduction of pathogens by the chlorination process in the system.

**Table 39. Infection risks during an outbreak and there is with chlorination**

| **Pathogens** | **$Log_{10}$- reduction by Chlorination** | **Chlorination with 67 minutes contact time** | |
|---|---|---|---|
| | | **Daily infection risk** | **Annual infection risk** |
| *Campylobacter* | 7.5 | 0.00E+00 | 5.51E-08 |
| EHEC | 7.43 | 0.00E+00 | 8.70E-10 |
| *Salmonella* | 7.43 | 0.00E+00 | 3.00E-14 |
| Norovirus | 2.04 | 1.20E-11 | 1.43E-07 |
| Adenovirus | 2.04 | 1.30E-07 | **1.98E-03(49)** |
| Rotavirus | 2.04 | 1.30E-10 | 1.69E-06 |
| *Cryptosporidium* | 0 | 4.90E-08 | 3.69E-06 |
| *Giardia* | 0.1 | 9.40E-12 | 9.02E-10 |



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