CHALMERS

Development of Three-Dimensional Hydrodynamic and Water Quality Model of Göta Älv River

Microbial impacts from tributaries Grönån and Gårdaån on the raw water intake at Lärjeholm

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

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Master's Thesis 2012:8

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Cover:
Prospect over the Göta Älv river, close to the city of Gothenburg.

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ABSTRACT

Limited information on microbe contribution from non-anthropogenic sources to Göta Älv exists. This study aimed to investigate the microbiological impacts on Göta Älv from the tributaries Gårdaån and Grönån. For this purpose, 10 litre water samples were collected on June 8th, July 6th and August 3rd 2011 in the tributaries and were analysed for *E. coli*, somatic coliphages and *Norovirus* GGI and GGII. A three-dimensional hydrodynamic model over Göta Älv from Lilla Edet to Gothenburg harbour was set up using software MIKE 3. The hydrodynamic model used data on geophysical, hydrological, meteorological and water properties conditions to form up a representation of Göta Älv during the period May 25th to August 17th 2011. Validation of the hydrodynamic model showed good correlation with measurements. For the microbiological model the software ECO Lab was used to simulate inactivation of the indicator organisms *E. coli* and somatic coliphages. The indicator inactivation was assumed to depend on water temperature, salinity and solar radiation intensity. For *Norovirus*, a no decay assumption was made due to lack of inactivation data and since the detection method qRT-PCR yield a total count of both active and inactive RNA strains. Decay conditions were superimposed on transportation of microbes from the two tributaries and upstream inflow at boundary Lilla Edet. Model results at raw water intake at Lärjeholm were compared with measurements to provide information of contribution from the tributaries compared to background levels from Lilla Edet.

Levels of *E. coli* and somatic coliphages were acquired from all sampling occasions. *Norovirus* levels were at all times below detection limit of 47 RNA-strings/100 ml for the tributaries samples. The modelled levels of *E. coli* at Lärjeholm account for 45% of the measured levels. Results from microbiological model indicate that the two tributaries are not significantly affecting level of microbes at Lärjeholm. Less than 0.5% of the modelled levels of *E. coli* could be derived from the tributaries, while Lilla Edet turned out to be the main contributor. The model presents similar results for *Norovirus* and somatic coliphages as for *E. coli*.

Keywords: hydrodynamic model, water quality model, *Norovirus*, *E. coli*, somatic coliphages, sampling, transportation, inactivation, sensitivity analysis

Utveckling av Tredimensionell Hydrodynamisk och Vattenkvalitetsmodell av Göta Älv

Mikrobiell påverkan ifrån biflödena Grönån och Gårdaån på råvattenintaget vid Lärjeholm

Examensarbete inom *Geo and Water Engineering*

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Avdelningen för Vatten Miljö Teknik

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SAMMANFATTNING

Endast begränsad information om nivåerna av tillförda mikrober från icke-antropogena källor till Göta Älv finns. Denna studie syftade till att undersöka den mikrobiologiska påverkan på Göta Älv från bifloderna Gårdaån och Grönån. För detta ändamål har 10-liters vattenprover samlats in den 8 juni, 6 juli och 3 augusti 2011 i bifloderna, vilka analyserades för *E. coli*, somatiska kolfager och *Norovirus* GGI och GGII. En tredimensionell hydrodynamisk modell över Göta älv från Lilla Edet till Göteborgs hamn utformades med programvaran MIKE 3. Den hydrodynamiska modellen använder uppgifter om geofysiska, hydrologiska, meteorologiska tillstånd och vattenegenskaper för att bilda sig en representation av Göta älv under perioden 25 maj till 17 augusti 2011. Jämförelser av resultat från den hydrodynamiska modellen visade godtagbar korrelation med data ifrån mätningar. För den mikrobiologiska modellen användes programvaran ECO Lab för att simulera inaktivering av indikatororganismer *E. coli* och somatiska kolifager. Indikatorernas inaktivering antogs bero på vattentemperatur, salthalt och solstrålningsintensitet. *Norovirus* antogs inte inaktiveras med anledning av brist av inaktiveringsuppgifter och eftersom detektionsmetoden qRT-PCR ger ett totalt antal av både aktiva och inaktiva virus-RNA. Inaktiveringsvillkoren överlagrades på transporten av mikrober från de två biflödena och även inflödet vid modellgränsen Lilla Edet. Modelleringsresultat vid råvattenintaget vid Lärjeholm jämfördes med mätningar för att ge information om bidrag från biflödena i förhållande till bakgrundsnivå från Lilla Edet.

Halterna av *E. coli* och somatiska kolifager förvärvades från alla provtagningstillfällen. Nivåerna av *Norovirus* var hela tiden under detektionsgränsen på 47 RNA-strängar/100 ml för samtliga prover ifrån biflödena. Modellerade halter av mikrober vid Lärjeholm uppgick till 45% av de uppmätta halterna. Resultaten från den mikrobiologiska modelleringen indikerar att de två biflödena inte märkbart påverkar nivåre av mikrober vid Lärjeholm. Mindre än 0.5% av de modellerade nivåerna av *E. coli* kunde härledas ifrån biflödena, medan Lilla Edet visade sig bidra med huvuddelen av nivåerna. Modellen ger likvärdiga resultat för *Norovirus* och somatiska kolifager som för *E. coli*.

Nyckelord: hydrodynamic model, water quality model, *Norovirus*, *E. coli*, somatic coliphages, sampling, transportation, inactivation, sensitivity analysis

Contents

Preface

In this study, hydrodynamic and microbiological modelling of norovirus, *E. coli* and somatic coliphages in Göta Älv has been performed during May to August 2011. Sampling, data acquisition and modelling for the time period resulted in the contributions from the tributary rivers Grönån and Gårdaån at Lärjeholm raw water intake. The project was commissioned by the Department of Water Environment Technology at Chalmers University of Technology, Sweden. Supervisor of the study was Thomas Pettersson, Project Manager, WET. The project was co-founded by the VISK project, which is a three-year EU project to reduce the society's vulnerability to waterborne virus diseases in a changing climate.

Water samples were conducted with appreciated assistance of the Environmental Laboratory at the Department of Civil and Environmental Engineering at Chalmers University of Technology. Also, our thanks go to the Rope Cording Museum (Repslagarmuséet) in Älvängen and the Björner family in Lödöse, who helped us with the placement and protection of sampling devices. Furthermore, this study could not have been performed without the help with data acquisition from SMHI, Vattenfall, Gothenburg Water Authority (Göteborg Vatten), Administrative Board of Västra Götaland County (Länsstyrelsen i Västra Götalands Län), Gothenburg Region Municipal Association (Göteborgsregionens kommunalförbund), Swedish Geotechnical Institute (Statens Geotekniska Institut), Gothenburg City (Göteborgs Stad) and Göta Älv Water Conservation Association (Göta Älvs Vattenvårdsförbund). Further our thanks go to our supervisor Thomas Pettersson and Lic. Ekaterina Sokolova, WET, for their assistance with background information and help with modelling procedures.

Finally, thanks to the Ryhov County Hospital in Linköping and Lackarebäck Water Laboratory for their meticulous analysis of *Norovirus* and faecal indicators respectively.

Göteborg November 2011

Saeed Mokhlesi

Andreas Öhrman

1 Introduction

Access to clean drinking water is one of the largest health issues in the world today. The sources for raw water supply are under constant pressure from an array of contaminations derived from chemical and biological sources. The microbial contamination is the largest concern in terms of drinking water quality, and a large part of the pathogenic microbes originate from faecal matter. Usually the risks posed at the drinking water supplies are known and the treatment plants in Sweden are supposed to be well equipped for removing most of the contaminations from drinking water. However, changes in precipitation patterns and temperature are changing the loads of contaminants in the surface water supply systems. Increased rainfall are transporting higher amounts of non-point source contaminants, and more frequent extreme weather events are causing sewage from waste water treatment plants to overflow more often; releasing potentially harmful microorganisms into the water systems. These increases of pathogens may exceed the treatment efficiency capacity and temporarily render the water source unfit for drinking water. The microbial pathogens mainly cause gastrointestinal diseases and presence in drinking water can cause waterborne disease outbreaks.

The studied river Göta Älv is raw water supply for several municipalities in the mid-western Sweden. 700 000 people are connected to the drinking water networks supplied by Göta Älv (Åström and Pettersson, 2007) and the treated waste water from the upstream municipalities are released into the river. Recent outbreaks of water spread diseases in Europe have actualized the risks to the raw water supplies. In 2010, four cases of waterborne outbreaks of *Norovirus* in Sweden have been confirmed (Swedish Institute for Communicable Disease Control, 2011a). Expected future climate change might result in higher levels of faecal microbes in the drinking water sources and pose increased risks to human health. Virus and bacteria status is not standard in environmental reporting and little is known about the quantities of virus originating from the different sources in Göta Älv.

1.1 Aim

This thesis aims at studying the contribution from tributaries Gårdaån and Grönån to *E. coli,* somatic coliphages and *Norovirus* concentrations at the raw water intake at Lärjeholm in the river Göta Älv. In order to execute the investigation a model to assess the impact of the microbes on the raw water intake at Lärjeholm were developed. Further, an investigation of the applicability of *E. coli* and coliphages as indicators for *Norovirus* in Göta Älv was carried out. Last, a future scenario was investigated with a microbiological risk assessment perspective for Göta Älv as a raw water source.

1.2 Method

The thesis includes (i) sampling of tributaries Gårdaån and Grönån to obtain data on microbial concentrations and (ii) hydrodynamic and microbiological modelling of contamination fate and transport in the river Göta Älv. The samples from the studied tributaries were collected at three occasions using sampling devices ISCO 3700 and ISCO 6700 for collection. The samples were analysed for *Norovirus* at Ryhov county hospital water laboratory and for *E. coli* and somatic coliphages at Alelyckan water

laboratory in Gothenburg. A three-dimensional hydrodynamic model of the river Göta Älv was constructed using MIKE 3 software. Input data for the hydrodynamic model of the river was acquired from diverse authorities. Literature review was conducted to obtain information on the behaviour of virus and indicator organisms in fresh water. Furthermore, a microbiological model ECO Lab was used together with the hydrodynamic model to simulate fate and transport of virus and faecal indicators in the river Göta Älv. Finally, modelled results were compared to field observations in order to investigate the microbial impact at Lärjeholm water intake from the studied tributaries.

1.3 Delimitation

Geographically, this study is limited to the Göta Älv River from the hydro power plant in Lilla Edet in the north to Gothenburg harbour in the south. Further, this study is only considering conditions from May 25th to August 17th, constricting hydrodynamic model and microbiological inactivation to summer conditions. The faecal indicators studied are restricted to *E. coli* and somatic coliphages and of viruses only *Norovirus* is included. No validation or calibration of the hydrodynamic model was executed, nor was the microbiological model. Only comparison with measured and modelled data at some locations along the river was carried out.

2 Background

2.1 Study area

The study area is a part of the river Göta Älv from the town Lilla Edet to the raw water intake at Lärjeholm, a distance of 42 km. Göta Älv is the largest river in Sweden with a watershed area of approximately one fifth of Sweden. Upstream the river originates from Lake Vänern, running through the cities Vänersborg and Trollhättan to Lilla Edet. The river upstream of Lilla Edet is running through both densely urbanized and cultivated land, also with a large part of forest and natural landscape. The river continues south from Lilla Edet and at Kungälv the river branches out into Nordre Älv (south-western branch) and Göta Älv (continues south) as displayed in Figure 2-1.

Lake Vänern is an important maritime shipping area and also popular for recreational maritime activities, as is Göta Älv. Further, downstream of Lilla Edet the landscape around the river changes towards more cultivated land and less natural forest, still with urbanized areas and also more industrial and shipyard activities. The daily mean flow in Göta Älv from Lilla Edet for the whole year is about 550 m^3/s and varies strongly due to controlled release at Lilla Edet water power plant. Hourly min, mean and max flow for each month during the study period at Lilla Edet is presented in Table 2-1.

Table 2-1: Hourly min, mean and max flow [m3/s] during 2011 in Göta Älv at Lilla Edet water power plant

Month	Minimum	Mean	Maximum
May	135	264.6	518
June	142	356.7	655
July	144	540.6	657
August	147	547.5	685

Along the river from Lake Vänern to Gothenburg harbour the water is used as raw water source for the surrounding municipalities' drinking water and also as recipient for discharges from the waste water treatment plants. The wastewater treatment plants are however equipped with overflow systems in case of overload of stormwater due to heavy rain and insufficient treatment capacity.

The flow in Göta Älv is regulated at several locations (Figure 2-1). These regulators control the flow for power generation and sluice purposes. For this project only the flow regulators in Lilla Edet and at Ormo, in the river branch Nordre Älv, are of interest. Raw water abstracted at the intake at Lärjeholm is used for drinking water supply of approximately 600 000 people (Gothenburgs City, 2011a).

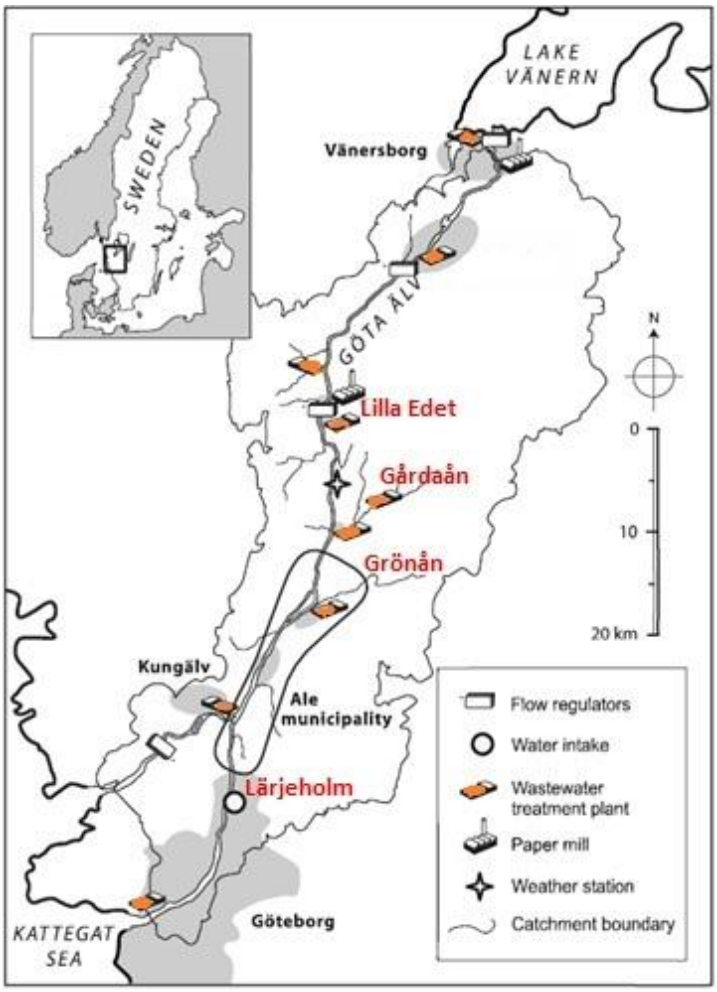

Figure 2-1: Göta Älv from Lake Vänern to Gothenburgs harbour estuary with catchment area and features along the run (Åström, 2011).

The Göta Älv river valley consists of marine clay deposited during and after the latest ice age. At times of snow melting and heavy rainfall the clay lack the capacity to infiltrate all water, which results in surface run-off, especially when the clay layers are already saturated (Göta Älvs Vattenvårdsförbund, 2011). A soil profile of Göta Älv river valley is presented in Figure 2-2.

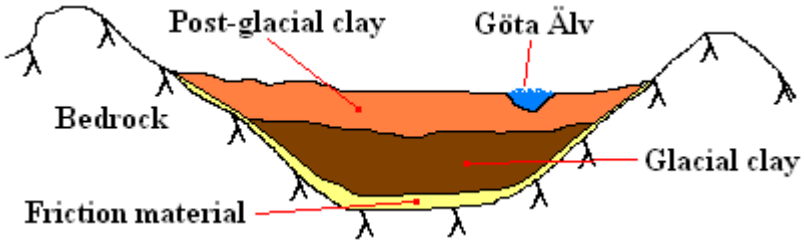

Figure 2-2: Schematic soil profile for Göta Älv River valley.

Several tributaries contribute to the flow in Göta Älv, though the bulk part of the flow originates from Lake Vänern. The tributaries investigated in this study are Grönån and Gårdaån. Both tributaries are located to the east of Göta Älv and are presented in chapters 2.1.1 and 2.1.2 respectively.

2.1.1 Grönån

Grönån estuary is located 25 km upstream Lärjeholm water intake and drains 197.5 km^2 of the Göta Älv catchment area (Figure 2-3). The tributary flows into Göta Älv at the town Älvängen surrounded by extensive farmland, which further upstream turns into forested hilly terrain.

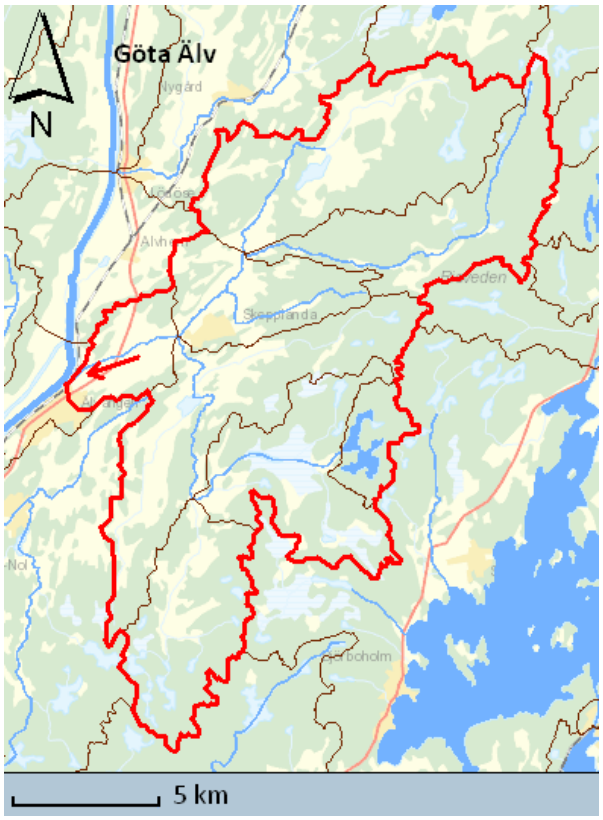

Figure 2-3: Grönån catchment area and inflow into Göta Älv (red arrow) (modified from VISS, 2011)

The flow in Grönån is acquired from SMHI (2011a) and is not measured, but modelled from precipitation and land use data. The mean, minimum and maximum flows in the tributary are displayed in Table 2-2 and comprises of average mean flow during the period 1990 to 2010.

Table 2-2: Modelled minimum, mean and maximum flow in Grönån, 1990-2010 (SMHI, 2011a)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Min	0.75	0.47	1.48	0.50	0.25	0.16	0.15	0.15	0.15	0.19	1.13	0.93
Mean	6.28	4.59	4.52	3.03	0.87	0.50	0.56	0.65	1.37	3.56	5.42	5.47
Max	12.0	11.5	8.45	11.8	2.94	1.60	3.11	2.14	4.87	9.43	13.2	12.7

2.1.2 Gårdaån

The tributary Gårdaån flows into Göta Älv 23 km upstream of Lärjeholm water intake through Lödöse town. Gårdaån drains 60.4 km^2 though sparsely urbanized farmland and forest area. The catchment area is similar to that of Grönån, except for a waste water treatment plant 7 km upstream of the tributary estuary (Figure 2-4).

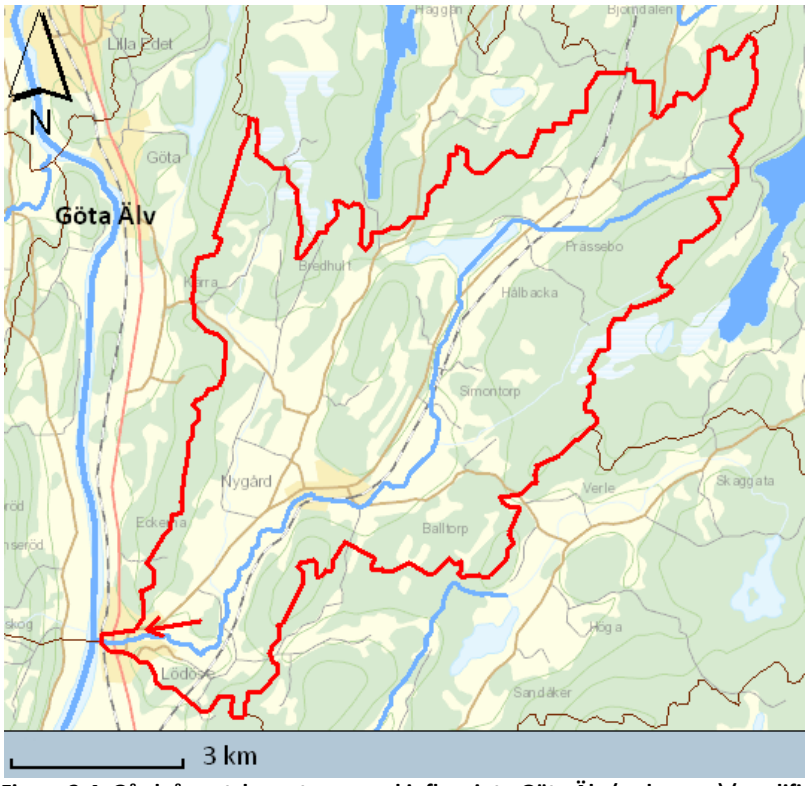

Figure 2-4: Gårdaån catchment area and inflow into Göta Älv (red arrow) (modified from VISS, 2011)

Mean, minimum and maximum flow at the inflow to Göta Älv is displayed in Table 2-3 and is also comprised of modelled average mean flow during the period 1990 to 2010 (SMHI, 2009b).

Table 2-3: Modelled minimum, mean and maximum flow in Gårdaån, 1990-2010 (SMHI, 2011b)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Min	0.21	0.11	0.36	0.11	0.05	0.03	0.03	0.03	0.03	0.04	0.15	0.25
Mean	1.66	1.21	1.20	0.79	0.21	0.11	0.12	0.10	0.26	0.79	1.37	1.43
Max	3.13	3.20	2.21	3.16	0.78	0.34	0.65	0.30	0.85	2.36	3.48	3.75

2.1.3 Ecological and chemical status

Göta Älv is used for many purposes and has several different natural values along the river run. Parts of the river are classified as protected area with Nature 2000 SPA system for risks to birds and species and habitats. This legislation is set up from European Union directives and aims to protect sensitive and important areas for diversity and endangered species (Swedish Environmental Code, 1998). Furthermore, Göta Älv is important as fish water, salmon among others, and Grönån is considered as a birthing ground for some fish species. Moreover, mussel bed and urban water directives protect parts of the river.

An overall summary of the ecological and chemical status of the river and tributaries is provided in Table 2-4. The qualitative status classification Good-Moderate-Poor describes the current status and estimated anthropogenic effects on the environment (VISS, 2011). Further, it is the strictest environmental legislation that governs the allowed pollution concentrations. In this study it is the Swedish recommended threshold values for drinking water sources.

Table 2-4: Overall ecological status for Göta Älv and studied tributaries (VISS, 2011)

Area	Chemical status except mercury	Mercury status	Ecological status	Eutrophicated	Acidified
Göta Älv	Poor	Poor	Moderate	Yes	No
Grönån	Good	Poor	Good	No	No
Gårdaån	Good	Poor	Poor	Yes	No

There are no current guidelines or legislations to include virus when investigating environmental status in Sweden. Göta Älv is however monitored for *E. coli* and total coliforms. In 2010 the guideline levels were exceeded in 1% of the samples for *E. coli* and in 5% for total coliforms at Lärjeholm. The pH-level in the river is stable around 7.4 ± 0.2 (Göta Älvs Vattenvårdsförbund, 2011). The Solar radiation intensity in Gothenburg during the studied period ranged between 0 and 0.89 kW/m^2 (Gothenburg City, 2011b).

2.1.4 Reference systems

In Sweden there are several different height systems to measure elevation over sea level in use. National reference systems have been set up and modified since 1892, and in some locations the first reference system RH00 is still employed. The zero level in RH00 is related to the water level in Stockholm the year 1900. The second reference system, RH70, relates to measurements conducted from 1951 to 1967 and includes correction for the land rising. RH70 is also in use in some areas. In 2005 a new reference system was introduced, RH2000, intended to become national standard (Lantmäteriet, 2011). In addition to the national reference systems, several local systems are in use. Relevant for this study is GH88 which is in use in Gothenburg, although it will be replaced in 2012 with RH2000. For practical purposes, the RH systems use the same zero level, while the GH88 differs from the national system with a correction value of -9.953 meters (Winkler, 2011). For this study all elevations over the sea level are expressed in the RH2000 system.

2.2 Drinking water system in Gothenburg

Gothenburg drinking water system supplies approximately 600 000 consumers. Approximately 2 m^3/s of raw water is taken from Göta Älv at Lärje raw water intake, half of which is led directly to Alelyckan treatment plant. From there the water is distributed to the consumers. The rest is led through an underground tunnel to a pumping station at Härlanda tjärn and is pumped up to Lilla Delsjön. The connected lakes Lilla and Stora Delsjön act as reservoir for Gothenburg. These two lakes together with the reserve supply Lake Rådasjön are capable of supplying drinking water for 3 weeks if the raw water intake is closed down. From Stora Delsjön the water is led to Lackarebäck treatment plant and is delivered to the consumers (Figure 2-5) (Gothenburgs City, 2011).

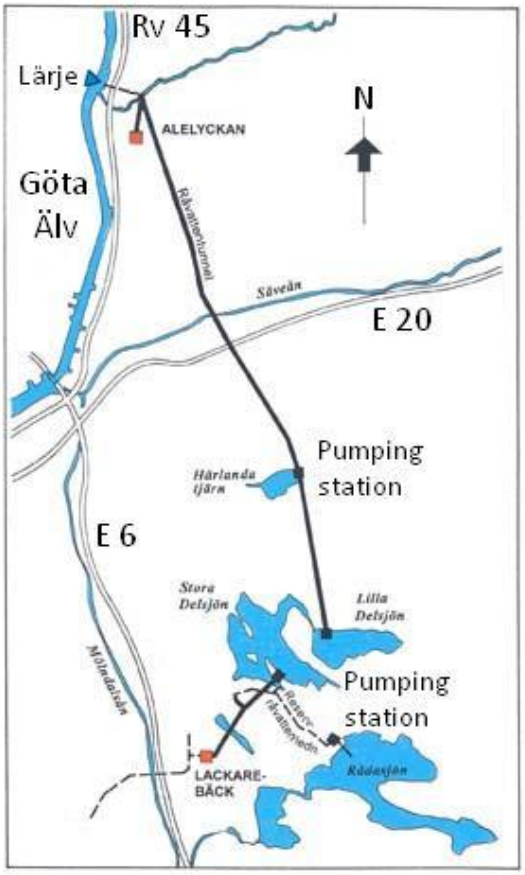

Figure 2-5: Gothenburg drinking water scheme with raw water intake at Lärjeholm, reservoir lakes and treatment plants Alelyckan and Lackarebäck (Gothenburg City, 2011a)

The drinking water treatment plants in Gothenburg (Alelyckan and Lackarebäck) use the same treatment steps and produce equally good drinking water. The raw water is treated in five steps; screening, pH adjustment, chemical precipitation, active carbon filtration and ph adjustment and chlorine disinfection (Gothenburgs City, 2011a). Suggested threshold values for *E. coli* in raw water in Sweden are 500 CFU/100 ml. and guideline value is 100 CFU/100 ml. For somatic coliphages a threshold value of 300 PFU/100 ml. and guideline value of 60 PFU/100 ml. are suggested (Friberg et al., 2010). The disinfection is performed by adding 0.15-0.25 mg/l of free chlorine to the drinking water before distribution (Gothenburgs City, 2011a).

The raw water intake at Lärjeholm is situated south of the river branch at Kungälv. To protect the raw water, a salt water screening facility has been erected at Ormo near Kungälv. Further, a water protection area has been established around the immediate surroundings of the raw water intake. During several occasions each year the raw water intake at Lärjeholm is closed due to contamination of Göta Älv. In 2010, 77% of the total intake closure time was caused by suspected or confirmed contamination by microorganisms. However, some cases of closures are due to salt water intrusion from the sea at high tides and low flows in the river (Göta Älvs Vattenvårdsförbund, 2011).

To enable intake closure, several control stations are located upstream and at Lärjeholm the water is automatically tested for contaminants. Three times a week the river water is analysed for indicator organisms to warn for the presence of microbiological contamination. The annual occasions of closures and the total length

of closure time are displayed in Figure 2-6. Since the mid 1990's the total closure time has varied between 1500 and 2800 hours, corresponding to between 17% and 32% of the year (Göta Älvs Vattenvårdsförbund, 2011).

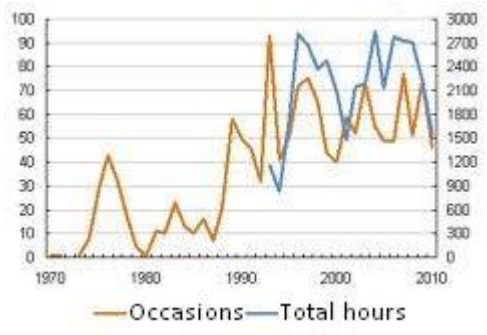

Figure 2-6: Annual shut down occasions and total shut down time for the raw water intake at Lärjeholm (Göta Älvs Vattenvårdsförbund, 2011).

2.3 Theoretical and mathematical background

The basic mathematical formulation and governing equations for developing both hydrodynamic and transport models are provided in this chapter. The equations governing the hydrodynamic model were mainly retrieved from MIKE 3 HD program documentation, developed by DHI (DHI, 2009a). Equations for the microbiological model were retrieved from ECO Lab program documentation (DHI, 2009b).

2.3.1 Hydrodynamic model

Governing equations are the momentum and continuity equations in Cartesian Co-ordinates, which are basically solved by incompressible Reynolds-averaged Navier-Stokes equations, or so called Shallow Water Equations. By using the shallow water equations the flow is considered not to have vertical acceleration (DHI, 2009a). The three-dimensional continuity equation solved by the model is written as equation (1).

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S \tag{1}$$

In equations (1) to (6) (x, y, z) is the Cartesian co-ordinates and (u, v, w) is the corresponding velocity components. The momentum equations in x and y directions are described as equations (2) and (3).

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial x}dz-\frac{1}{\rho_0 h}\left(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial x}\right)$$
$$+F_u+\frac{\partial}{\partial z}\left(\upsilon_t\frac{\partial u}{\partial z}\right)+u_s S \tag{2}$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial wv}{\partial z}=fu-g\frac{\partial \eta}{\partial y}-\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial y}dz-\frac{1}{\rho_0 h}\left(\frac{\partial s_{yx}}{\partial x}+\frac{\partial s_{yy}}{\partial y}\right)$$

$$+\mathrm{F}_v+\frac{\partial}{\partial \mathrm{z}}\left(\upsilon_{\mathrm{t}}\frac{\partial \mathrm{v}}{\partial \mathrm{z}}\right)+v_{\mathrm{s}}\mathrm{S} \tag{3}$$

Where f is the Coriolis parameter, υ_t is the vertical turbulent viscosity, η is surface elevation and h is the total water depth; ρ and ρ_0 is water density and reference water density respectively; p_a is the atmospheric pressure and u_s and v_s are the resulting discharge velocities; S is the point source related velocity magnitude and g is gravity acceleration; s_{xx}, s_{xy}, s_{yx} and s_{yy} are stress tensor components.

The program uses the cell centered finite volume method to discrete the shallow water equations. The UNESCO formula is used as equation of state for incompressible flow describing the relation between density, temperature and salinity (Equation (4)).

$$\rho = \rho(T, S) \tag{4}$$

The two last equations for the hydrodynamic model are the transport equations for the salinity and heat balance as equations (5) and (6).

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}}+\frac{\partial \mathrm{uT}}{\partial \mathrm{x}}+\frac{\partial \upsilon \mathrm{T}}{\partial \mathrm{y}}+\frac{\partial \mathrm{wT}}{\partial \mathrm{z}}=F_T+\frac{\partial}{\partial \mathrm{z}}\left(D_\upsilon\frac{\partial \mathrm{T}}{\partial \mathrm{z}}\right)+H+T_sS \tag{5}$$

$$\frac{\partial \mathrm{s}}{\partial \mathrm{t}}+\frac{\partial \mathrm{us}}{\partial \mathrm{x}}+\frac{\partial \upsilon \mathrm{s}}{\partial \mathrm{y}}+\frac{\partial \mathrm{ws}}{\partial \mathrm{z}}=F_s+\frac{\partial}{\partial \mathrm{z}}\left(D_\upsilon\frac{\partial \mathrm{s}}{\partial \mathrm{z}}\right)+s_sS \tag{6}$$

Where D is the turbulent diffusion coefficient and H is the heat exchange; T and T_s are temperature and temperature of the source respectively; s and s_s are salinity and source salinity; F_T and F_s are the horizontal diffusion of temperature and salinity.

Time integration of transport equations in MIKE 3 is performed using semi-implicit scheme (DHI, 2009a), this means that the program uses the explicit and implicit scheme for horizontal and vertical terms respectively. The transport process in rivers is expected to be dominated by advection because of the flow in the river. Lower order discretization can be sufficiently accurate and also can reduce the computational time significantly in this project (Ji, 2008). Furthermore, using the explicit scheme, the stability requirement must be taken in to account in which the Hydrodynamic Courant number (Cr) should not become more than critical Cr number, that is achieved by either selecting the appropriate time step interval or improving the mesh elements subjected to stability problem (DHI, 2009a).

2.3.2 Microbiological model

The fate and transport of a state variable is summarized with ordinary differential equations in ECO Lab. The Water quality template that has been used in this study uses the following first order inactivation formula to express the decay of microbes (Equation (7)).

$$\frac{dC}{dt}=-k*C \tag{7}$$

Where C is the concentration of the indicator, t is time in days and k is the decay rate for corresponding indicator (DHI, 2009b).

The decay of the faecal indicators was assumed to depend on three factors: salinity, light intensity and temperature as described by equation (8) from Mancini (1978; cited in Sokolova, 2011).

$$k = k_0 * \theta_S^{Sal} * \theta_I^{Int} * \theta_T^{(Temp-20)} \quad (8)$$

Where k_0 is the decay rate at 20 °C and 0 ‰ salinity, θ_S is salinity decay rate, *Sal* is the salinity in ‰, θ_I is the decay rate from light intensity, *Int* is the light intensity in kW/m^2 over depth, θ_T is the decay rate from temperature deviation from 20 °C and *Temp* is the water temperature.

To account for loss of light intensity over depth in the river, Secchi depth is employed. Beer's law (equation (9)) describe how the light intensity changes in the water column (DHI, 2009b).

$$f_z = f_0 * e^{-\mu * z} \quad (9)$$

Where f_0 and f_z is light intensity at the surface and at depth z in the river and μ is the extinction coefficient.

Decay for Norovirus is not available due to the inability to cultivate them (Hijnen et al., 2005; Duizer et al., 2003). Therefore a conservative model was run with no decay to study the advection and diffusion to the raw water intake. The decay expression used is described by equation (10).

$$\frac{dC}{dt} = -1 * C \quad (10)$$

3 Literature review

The behaviour of *Norovirus*, somatic coliphages and *E. coli* is presented with focus on the factors that affect their persistence in fresh surface water. Also the topic of climate change is reviewed for expected future scenario settings.

3.1 Virus and faecal indicators

Viruses are the smallest life form known, effectively consisting only of a nucleic acid and a protein shell. For drinking water production purposes raw water with small amounts of human pathogens is preferred, but often not available. In his study, Craun (1991) states that over 100 different types of viruses are present in sewage contaminated waters. Of these, only some are threatening human health in terms of risk of widespread infection in consumers. The most common viruses have human mortality rates below 1% in developed countries (Bosch, 1998; Craun et al., 2006). However, virus is still a major risk to the society due to the proportionally low amounts of viruses needed to infect humans. Also, a large amount of infected persons have great effect on the society with stress on health-care systems and the economy.

3.1.1 Norovirus

Also called Norwalk-like viruses, *Norovirus* belongs to the *Calicivirus* family and is divided into five genera (GG) from I to V. The human *Norovirus* are mainly found in GG I and II with some in GG IV (Schwab and Hurst, 2006). Over 100 of human *Norovirus* strains are circulating, among them the winter vomiting disease which annually affects thousands of people in Sweden. The symptoms are acute gastroenteritis with *Norovirus* as the largest source worldwide (Duizer et al., 2003). For *Norovirus* no zoonotic transmissions have been confirmed (Schwab and Hurst, 2006).

Human *Norovirus* has resisted all attempts of cultivation, and therefore nothing is known about the inactivation of infectious strains in nature (Schwab and Hurst, 2006; Duizer et al., 2004). Duizer (2004) argues that feline and canine calicivirus with similar replication site and transmission routes are suitable for studying *Norovirus* while Schwab and Hurst (2006) argue that poliovirus and Hepatitis A with similar RNA characteristics are appropriate. Viruses are unable to reproduce after they are excreted from the infected host and start to inactivate. Human excreta are more or less directly subjected to negative environmental conditions via the sewage systems. Therefore, the observed levels of *Norovirus* are both active and inactive viruses. The dominant factors that affect *Norovirus* survival in water are water temperature and UV exposure (Duizer et al., 2004). According to Ferguson et al. (2003), there is no common indicator suitable for all enteric viruses and the appropriate indicator must be selected according to its survival time in a specific environment and by considering several other factors. The survival of the virus correlates with the exposure length to the negative living conditions. Thus, the travel time and weather conditions are the most relevant factors for studying *Norovirus*. The main pathway for *Norovirus* infecting humans is the faecal-oral route red marked in Figure 3-1.

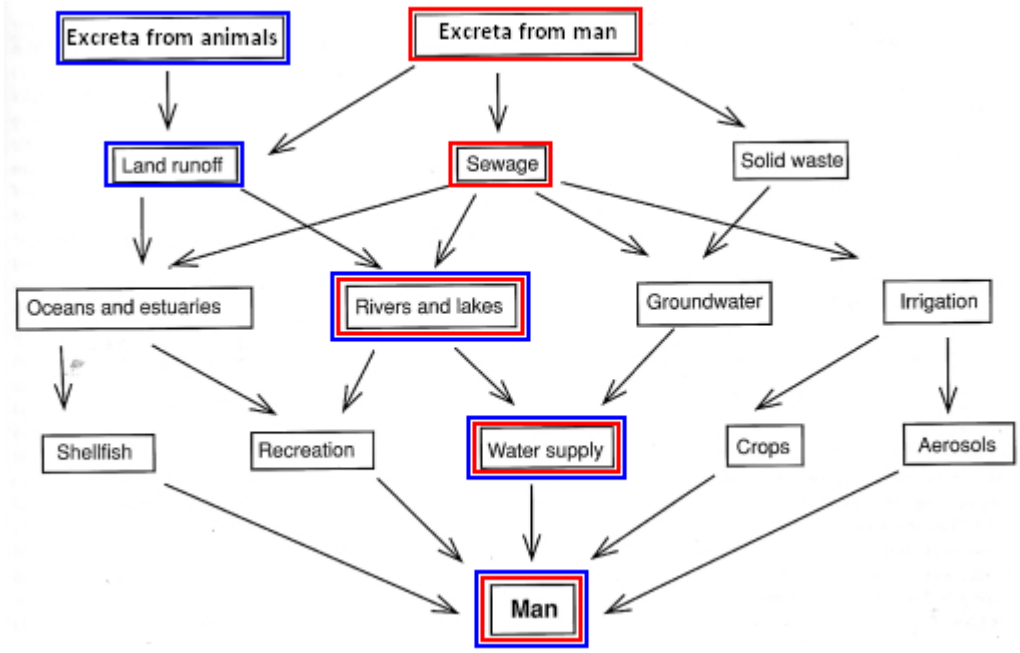

Figure 3-1: Pathways, faecal-oral route, for pathogens to humans (Modified from Craun, 1991). Red-marked pathway for *Norovirus* and blue and red for studied indicator organisms

The study of canine and feline calicivirus (Duizer et al., 2004) resulted in inactivation data in laboratory conditions for several factors. Of these thermal inactivation, pH stability and UV inactivation was considered important for this study. The results are displayed in Figure 3-2.

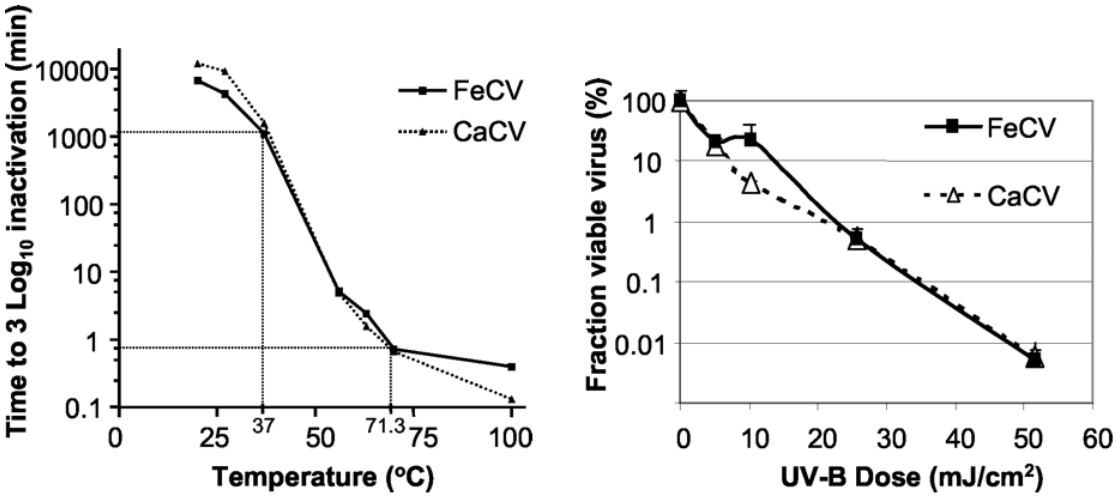

Figure 3-2: Inactivation of feline (FeCV) and canine calicivirus (CaCV) due to temperature and UV-radiation. The UV radiation test was executed at 0°C (Duizer et al., 2004)

The inactivation due to temperature show the time to induce a 3 $\log_{10}$ inactivation, i.e. the time to reduce the viable virus strains by 99.9 % (Figure 3-2). Inactivation of FeCV and CaCV due to pH around 7.2 is negligible (Duizer et al., 2004).

3.1.2 Faecal indicators

Today only *Escherichia coli* (*E. coli*) and total coliforms levels are continuously analysed in Göta Älv as indicators for faecal indicators in the raw water (Göta Älvs Vattenvårdsförbund, 2011). Scott et al. (2002) argues that *E. coli* is a good indicator

of faecal contamination since the concentration of *E. coli* often is higher and more easily detected than viruses and other pathogens. However, they suggest that total coliforms are limited in use as indicator due to differences in persistence from pathogenic microorganisms. Moreover, *E. coli* is not limited to humans, but is common in all warm-blooded animals. Therefore, a detection of *E. coli* cannot provide a conclusion about the presence of *Norovirus*. Bosch (1998) on the other hand argues that there are no good indicators that fulfil the criteria for an ideal indicator organism, other than the pathogen itself. Further, all groups of coliforms are known to re-grow in natural waters, making the quantitative aspects of indication difficult (Maier et al., 2000). Also, literature review by Hijnen et al., (2006) reports that a natural bacterium is more resistant to UV than lab-grown strains. This is supported by Sinton et al. (2001), who also includes somatic coliphages to that statement. Lastly, a study by Skraber et al. (2004) showed no correlation between coliforms concentrations and *Norovirus* GGII genome but correlation between somatic coliphages and NoV GGII. The pathways for the indicator organisms used in this study are marked in blue and red in Figure 3-1.

For this study, *E. coli* and somatic coliphages are used as indicators of faecal contamination. *E. coli* is a family of bacteria which among others include the 2011 medially noticed outbreak of EHEC in e.g. Germany (Kaper et al., 2004; Swedish National Board of Health and Welfare, 2011; Swedish Institute for Communicable Disease Control, 2011b). Also, a study by Sinton et al. (2002) states that up to 73 % of the total coliforms in sewage is made up of *E.* coli. Coliphages are viruses that infect *E. coli* (Harvey, 1997). Since the behaviour of the indicators in many aspects is site specific (Hijnen et al., 2006; Duizer et al., 2004) and no experimental study regarding inactivation was performed in this study, data obtained from a microcosm experiment for a recent project in the nearby Lake Rådsjön were used (Sokolova, 2011). The resulting inactivation parameters in a Chick first order decay model are displayed in Table 3-1.

Table 3-1: Time for 1 log10 decay (90 % reduction) of *E. coli* and somatic coliphages for different time of the year at lake Rådasjön in 2010 (Sokolova, 2011)

Faecal indicator	Regime	Month	Decay coefficient, k (/day)	Time for 90 % reduction T_{90} (days)	Curve fit, R^2
E. coli	Light	March	0.32	7.3	0.95
		August	0.25	9.2	0.44
		November	0.14	16.0	0.90
	Dark	March	0.13	17.3	0.78
		August	0.26	8.8	0.56
		November	0.16	14.2	0.82
Somatic coliphages	Light	March	0.14	17.0	0.98
		August	0.41	5.6	0.98
		November	0.42	5.5	0.83
	Dark	March	0.06	40.4	0.57
		August	0.17	13.3	0.75
		November	0.20	11.7	0.60

The survival time of *E. coli* and somatic coliphages are dependent on water temperature, salinity and light intensity. Warmer water, higher light intensity and higher salinity are increasing the rate of indicator inactivation (Sinton et al., 2002).

3.2 Climate change

The world climate is a very complex system of forces governed mainly by the energy of solar radiation that reaches the earth. Since the industrialisation of the western world, changes in several parameters of the global climate are not easily explained by natural causes alone. One of the more profound climate changes that have been studied is global warming and its effects. For this study the most interesting parameters is rising temperature, higher sea level and changes in precipitation patterns for the study area (IPCC, 2007). Data for historic changes and future scenario settings were acquired from the Intergovernmental Panel on Climate Change (IPCC) and SMHI centre of climate modelling, Rossby Centre. Figure 3-3 shows increasing global air temperature in the last century and increasing average sea level (IPCC, 2007).

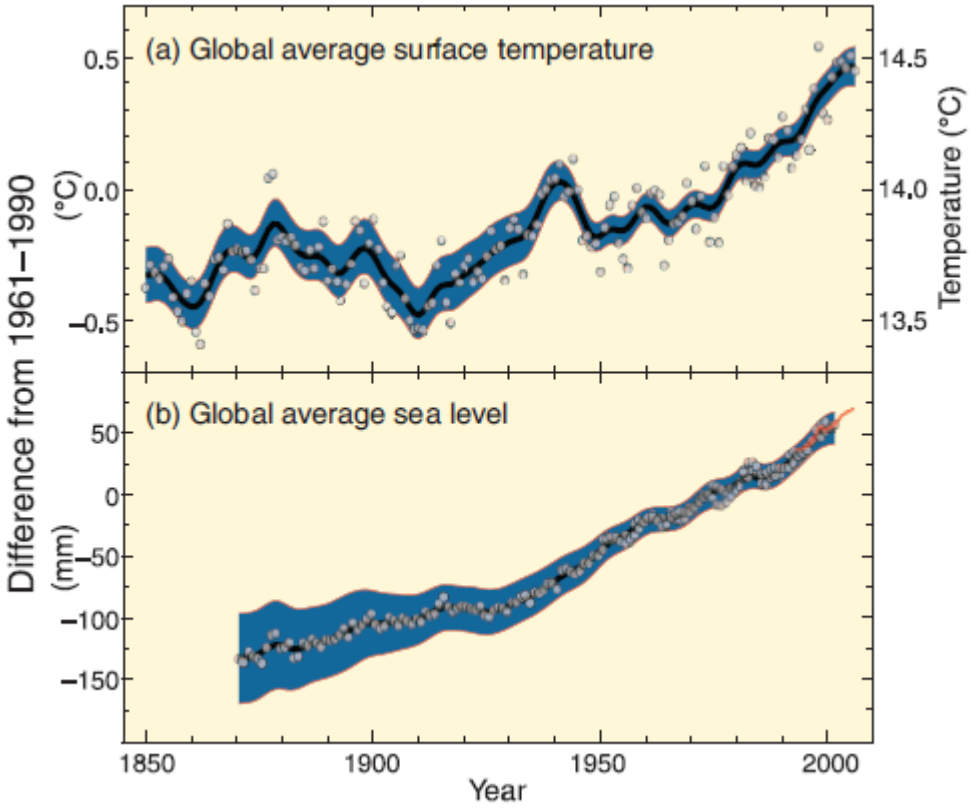

Figure 3-3: Historic change in global average surface temperature and global average sea level (IPCC, 2007)

In Sweden the land undergo a rise relative the sea level. Disregarding this, there has been a rise of the sea level relative the land rise in the southern parts of Sweden of approximately 20 cm from 1890 until 2010 (Figure 3-4).

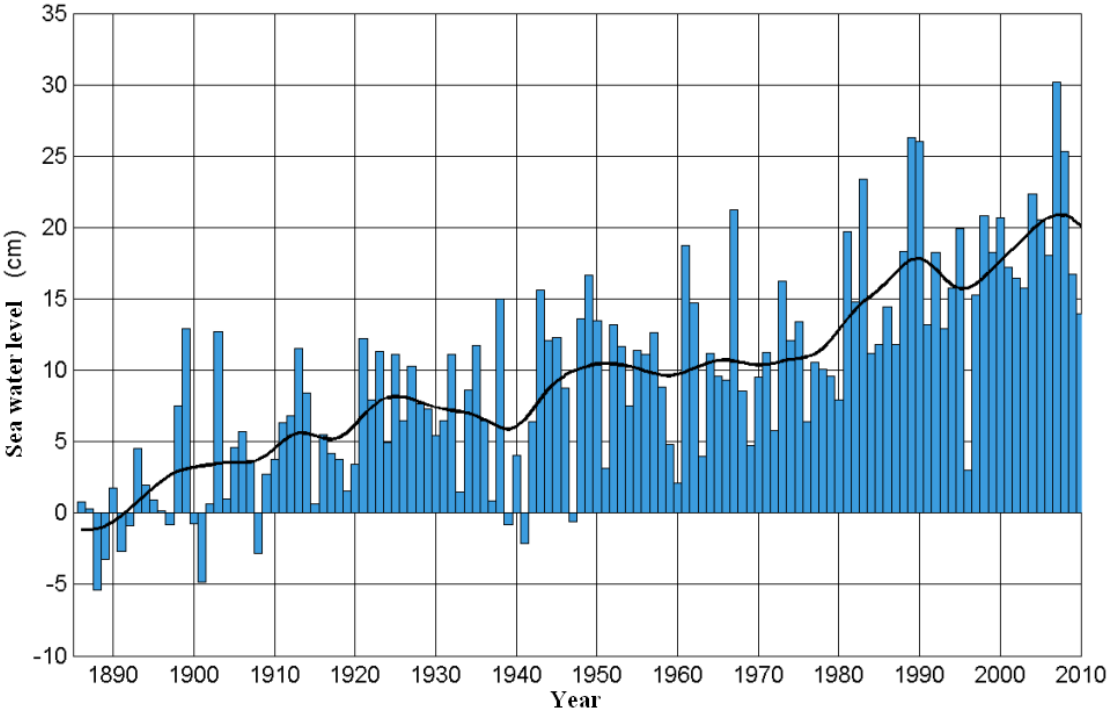

Figure 3-4: Sea water level change in Sweden from 1890 until 2010 relative the land rise (SMHI, 2011e)

3.2.1 Effects of changed climate

Changes in the climate systems, such as global warming, are caused by changes in the earth's energy balance. The driving forces are foremost solar radiation intensity reaching earth and the amount of greenhouse gases (GHGs) in the atmosphere. To account for the rising temperature the amounts of GHGs have been studied from ice core samples, providing data for several thousand years (Figure 3-5). As displayed, the post industrial increases in CO_2 and methane gas levels in the atmosphere is significant and are very likely caused by anthropogenic use of fossil fuels. The increase of GHGs leads to an increased level of retained heat from solar radiation and thus increased temperature (IPCC, 2007).

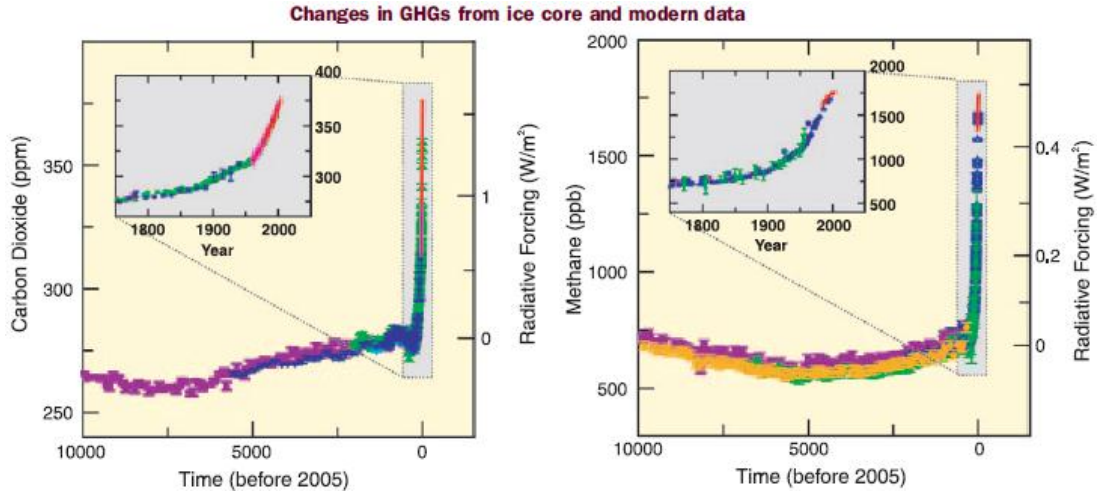

Figure 3-5: CO2 and methane gas levels in the atmosphere from 10 000 years back until 2005. Highlighted boxes for 1750 until 2005 (modified from IPCC, 2007)

3.2.2 Impacts and future scenarios

The global warming is expected to follow the recent patterns during the 21st century with further increased air temperature, higher sea water levels and increased precipitation in the study area. Also, more frequent extreme weather events are expected for the Scandinavian countries. The climate changes in the future scenarios are dependent on emission scenarios of GHGs (SMHI, 2011e; IPCC, 2007). Projected change relative 1961 – 1990 data in precipitation for the study area is presented in Figure 3-6 (SMHI, 2011e).

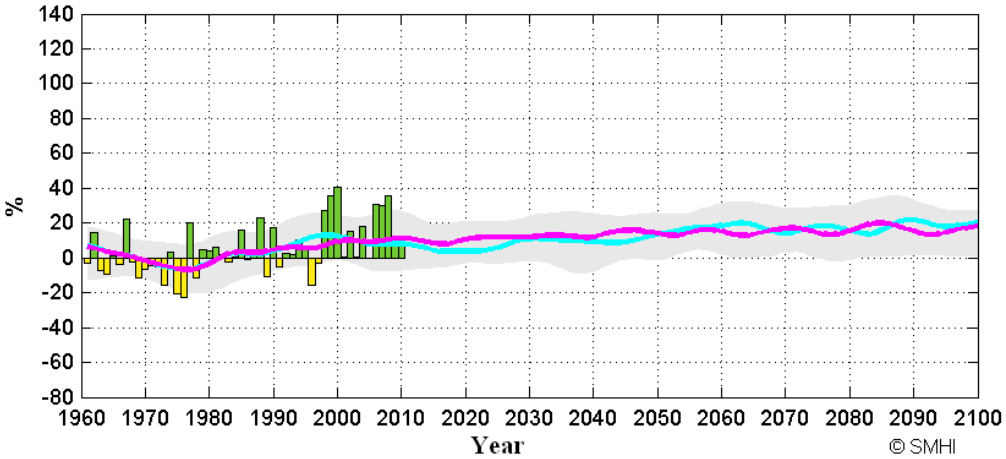

Figure 3-6: Measured and modelled data of precipitation in Västra Götaland from 1960 until 2100, relative mean value for 1961 to 1990 (SMHI, 2011e).

IPCC projects that the change in run-off in the study area is an increase of 10% to 20% until the year 2100 compared to 1980 – 1999 data (IPCC, 2007). Expected change in temperature relative 1961 – 1990 data is presented in Figure 3-7 (SMHI, 2011e).

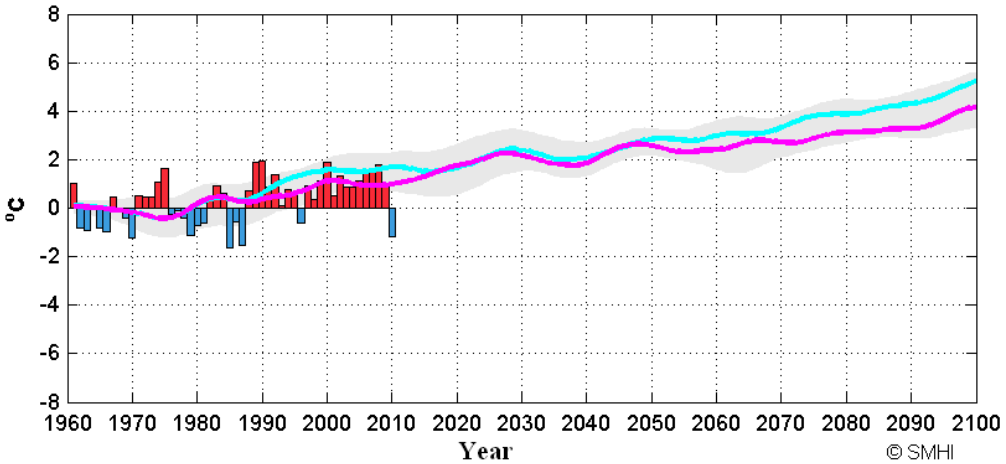

Figure 3-7: Measured and modelled data of air temperature in Västra Götaland from 1960 until 2100, relative mean value for 1961 to 1990 (SMHI, 2011e).

IPCC estimates that in western Sweden the temperature will increase compared to 1980 – 1999 data with between 2.5 and 4.5 degrees until 2100 (IPCC, 2007). The sea water temperature is expected to rise with 1.5 to 2.5 degrees at Sweden. As for rise of sea water level the projected change by ICPP is between 0.18 to 0.59 cm (IPCC, 2007), while SMHI do not present any estimations. The sea water rising does not include additional sea water from melting polar ice caps. In all, the expected future changes according to IPCC and SMHI are equivalent.

4 Methodology

To investigate the impact of *E.* coli, somatic coliphages and *Norovirus* from Grönån and Gårdaån at Lärjeholm water intake, the study was conducted in four main steps:

- Sampling
- Set-up of hydrodynamic model
- Validation of hydrodynamic model
- Set-up of microbiological model
- Analysis of resulting levels of microbes at Lärjeholm and future scenario

Methodology process overview is presented in Figure 4-1.

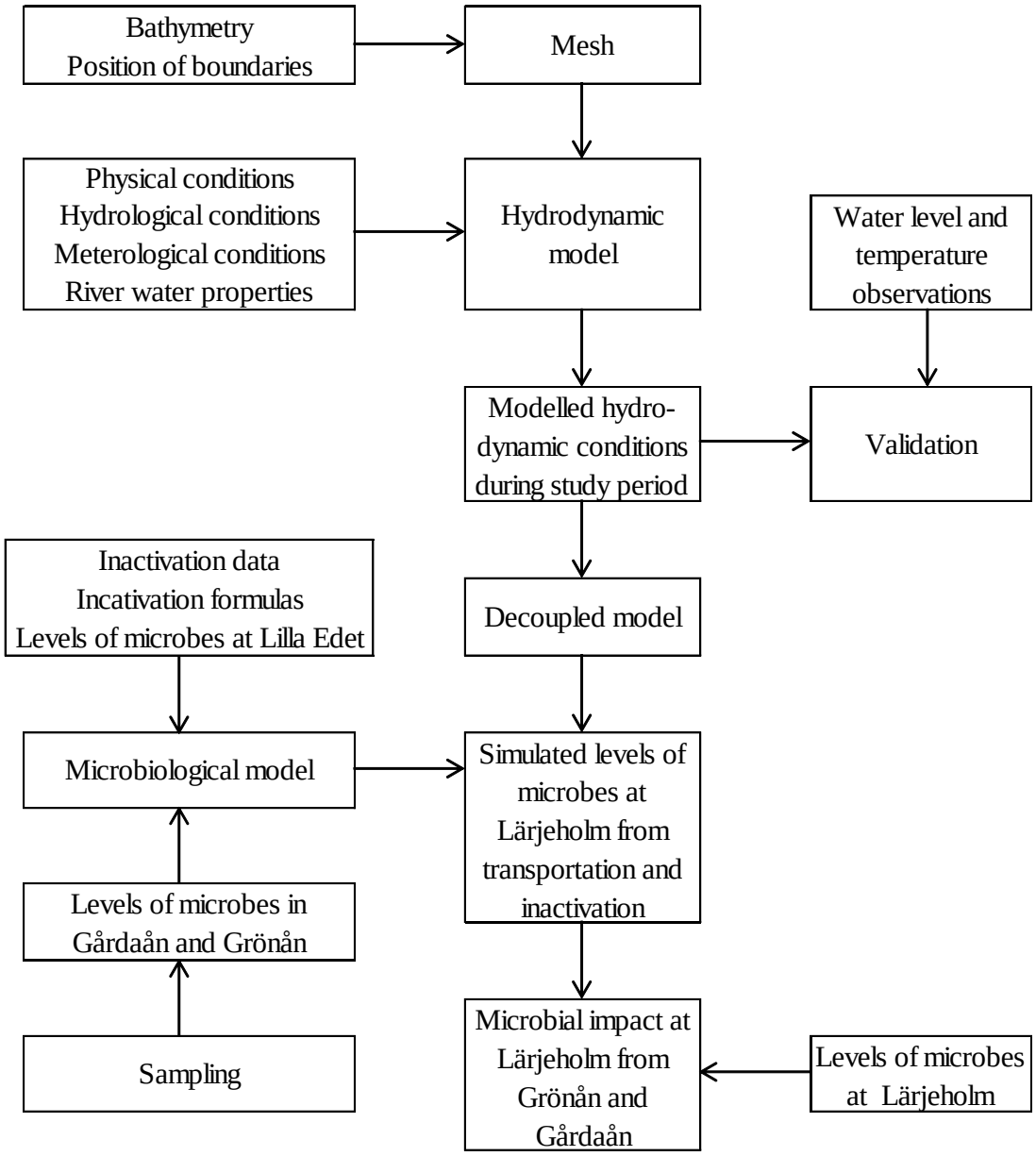

Figure 4-1: Methodology process overview

4.1 Sampling

Water samples were collected at three occasions in both tributaries during the period from June to August 2011 with 4 week intervals. 10 litre samples were collected in PVC bottles close to the estuaries into Göta Älv and were analysed for virus and faecal indicators. The first sampling occasion were preceded by dry weather for some weeks but the following two occasions were preceded by rainfall.

Two types of samples were collected; grab samples and 24 hour multiplex samples. At the first sample occasion at June 8th, grab samples were gathered. The grab samples were collected at one time at 0.5 meters depth in the middle of the rivers. The 24 hour multiplex samples were however collected in two different styles, but at the same locations as the grab samples. The sampler device is presented in Figure 4-2.

On July 6th sampling occasion the samplers were started at 09.00 July 5th, taking 48 consecutive samples each half hour until 09.00 at the noted sampling date. A malfunction in the ISCO 6700 sample device resulted in a 9 litre grab sample mixed with 1 litre of 24 hour multiplex sample from unknown time in the sample interval.

The samples noted as collected on August 3rd were set up to start 09.00 the 2nd, taking 24 consecutive samples each hour until 09.00 the day after. However, here the ISCO 3700 sample device malfunctioned and a grab sample was conducted.

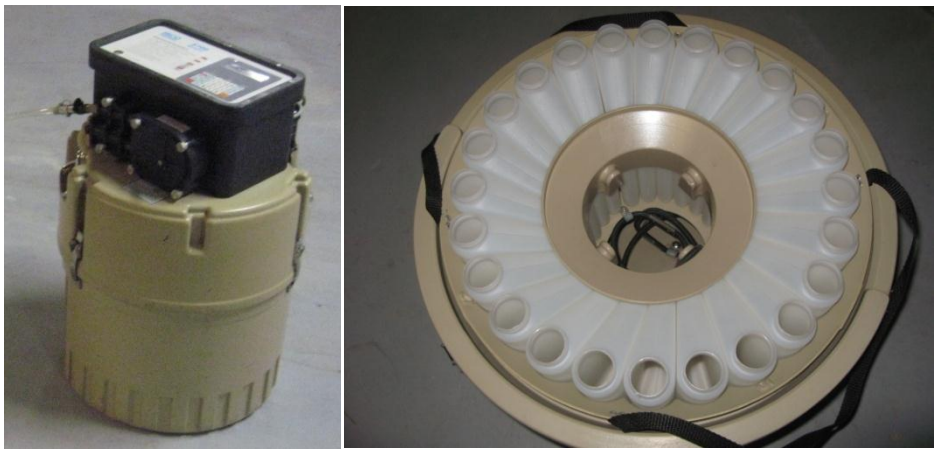

Figure 4-2: Left picture: Sample device ISCO 3700. Right picture: Opened to display the 24 containers for multiplex sampling

4.1.1 Gårdaån

The sampling in Gårdaån was conducted about 150 meters from the estuary into Göta Älv (sampling location marked with a red dot in Figure 4-3). The river depth varies with recent amounts of precipitation between 1 and 1.5 meters and the width is about 4 meters at the sampling location. The sampling suction tube was fastened to a stick in the middle of the river at 0.5 meters depth from the river surface.

Figure 4-3: Sampling location at Lödöse for Gårdaån sample (modified from Eniro.se).

The sampling device used in Gårdaån was an ISCO 6700 with 24 one litre PVC bottles for multiplex sampling. Table 4-1 displays the type of sample and circumstances at the three sampling occasions.

Table 4-1: Sample dates, labels, type and circumstances in Gårdaån.

Sample occasion	Sample date	Sample name	Type of sample	Circumstances
1	2011-06-08	S2	Grab sample	Small flow, calm/still water
2	2011-07-06	S4	Grab sample[a]	Large flow, troubled water
3	2011-08-03	S6	24 h multiplex	Large flow, troubled water

a) The S4 sample was disturbed by using 1 litre of 24 h multiplex sampling with 9 litres of grab sample.

4.1.2 Grönån

Figure 4-4: Sampling location at Älvängen for Grönån sample (modified from Eniro.se).

The samples in Grönån were taken about 50 meters from the estuary into Göta Älv (sampling location marked with a red dot in Figure 4-4). The river depth is about 2

meters and the width is 12 to 15 meters at the sampling location. The sampling suction tube was fastened to a weight anchored to the bridge spanning the river at 0.5 meters depth in the middle of the river.

The sampling device used in Gårdaån was an ISCO 3700 with 24 500 ml PVC bottles for multiplex sampling. Table 4-2 displays the type of sample and circumstances at the three sampling occasions. The size of the river made ocular flow estimation impractical. Possibility of water intrusion from Göta Älv exists, but could not be established.

Table 4-2: Sample dates, labels, type and circumstances in Grönån.

Sample occasion	Sample date	Sample name	Type of sample	Circumstances
1	2011-06-08	S1	Grab sample	Calm water
2	2011-07-06	S3	24 h multiplex	Slow running water
3	2011-08-03	S5	Grab sample[a]	Slow running water

a) Grab sample due to sample device malfunction.

4.1.3 Microbiological analysis

The samples were collected within a few hours from the end of the sampling occasion and were stored at 4 degrees Celsius. Thereafter samples were sent to Ryhov county hospital's water laboratory for detection of *Norovirus*. Detection method used for *Norovirus* was real-time quantitative reverse transcriptase polymerase chain-reaction (qRT-PCR) (Dienus, 2011a). The analysis resulted in a total count of viruses, active or inactive (Loddler and de Roda Husman, 2005). However, the method is subjected to several problems and quality control issues, which affect the accuracy (Rochell and Schwab, 2006; Bustin and Mueller, 2005).

Analysis of *E. coli* and somatic coliphages were executed at Lackarebäck water laboratory with analysis methods SS-EN ISO 9308-1 for *E. coli* and SS-EN ISO 10705:2-2002 for somatic coliphages (LIVSFS, 2005) from the same batches of samples as for virus analysis.

4.2 Hydrodynamic model set-up

In order to simulate fate and transport of virus in the river hydrodynamic and microbiological modeling approach has been used. To simulate flow and water level variation in the river Göta Älv a three-dimensional hydrodynamic model was constructed using the Hydrodynamic Module in MIKE 3 with Flexible Mesh from Mike zero package developed by DHI. The hydrodynamic model was then used together with the Transport Module in order to study and simulate the transport of virus in river Göta Älv. The reader is referred to program manuals for detailed description of the module (DHI, 2009a; DHI 2009b). During the study many attempts have been made to develop the model as realistic as possible though some assumptions have been made, due to lack of data.

4.2.1 Mesh generation

The initial stage of hydrodynamic modeling requires the generation of a computational mesh for the domain. Mesh has a great impact on accuracy of modeling results to be as similar to reality as possible. The mesh file includes information about boundaries, bathymetry and water level.

In this study, the flexible mesh, which has been generated by Zhang (2009), is modified by mesh generator component of MIKE Zero package and re-used in order to model hydrodynamic flow in river Göta Älv. The irregular grid size is performed in the horizontal plane while a structured mesh is used in vertical domain so that the simulation time and accuracy of simulation result can be optimized (Mike 3HD User Guide, 2009a). The size of the elements from Lilla Edet to Nordre Älv was determined on the order of 100 m×70 m and smaller elements of 100 m × 25 m are used from Nordre Älv to Gothenburg harbor, such that to satisfy more detailed bathymetry in this area. Furthermore, the grid orientation is aligned to the direction of the river flow and the Mesh has been adopted with quadrangular in the middle and triangular on the shoreline elements in order to account for its large variation (Figure 4-5).

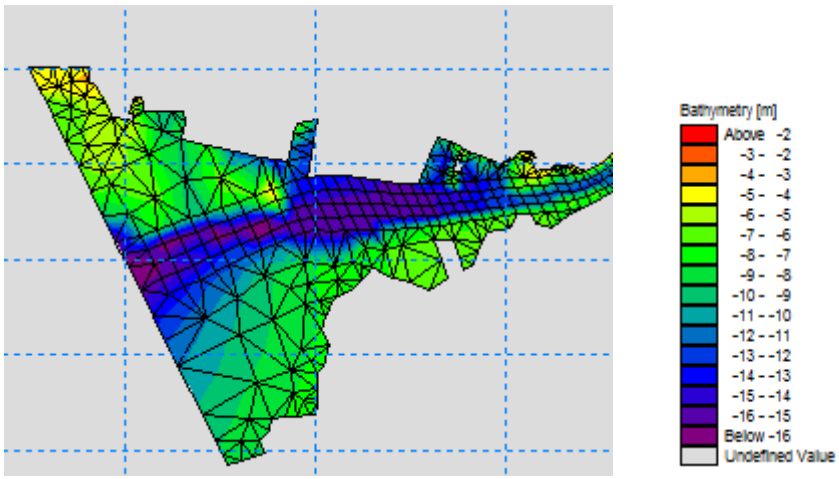

Figure 4-5: Generated mesh displaying water depth close to Gothenburg harbour

MIKE 3 uses Delaunay method for mesh generation in which the triangulation is being carried out based on the Triangle algorithm (DHI, 2009c). Maximum triangle area of 200 m^2 with no angels smaller than 30^o has been set up as limitations. The mesh consists of 5 vertical sigma distributed layers, 35900 nodes and 64725 elements. The mesh generation aimed at achieving a compromise between the accuracy of the result and the computational time. Furthermore, the natural neighbor interpolation method was used, which is expected to yield more accurate result than linear interpolation. The generated mesh close to the Gothenburg harbor boundary can be seen in Figure 4-5.

Interpolation of scatter data to the mesh nodes took 26255 seconds in situation of having maximum triangle area as 200 m^2 and using the natural neighbor interpolation method.

Accurate data on topography of the river together with bathymetry are necessary to generate the mesh. The Mesh that is used in this model was originally generated by Chen Zhang (2009) and further information about bathymetry and boundaries regarding the regeneration and adjustment of mesh file has been obtained from

Swedish Geotechnical Institute (SGI) and the Swedish Maritime Administration (Sjöfartsverket).

4.2.2 Forcing data

Setting up a flow model in MIKE 3 was performed through applying variety of variables and input in the program. The simulation period was determined to be from 25th of May to 15th of August to cover the period when the sampling events were performed, and also to account for natural variation of river.

Coriolis force appears when there is a large scale of water body such as ocean, which does not have significant influence on water level in river. However, the force was considered in simulation in order to increase the accuracy of the result while the increase in computational time was negligible. Also, the tidal variation was assumed to be negligible due to its small effect on hydrodynamics of the river over the selected time period. Table 4-3 describes other parameters and inputs used in hydrodynamic module.

Table 4-3: Parameters that govern the hydrodynamics in a MIKE3 simulation

Parameters	Description	Input value
Horizontal Eddy Viscosity	Smagorinsky formulation	0.28
Vertical Eddy Viscosity	K-epsilon formulation	
Bed Resistance Coefficient	Roughness height	0.05

Forcing data describe conditions that govern the behaviour of the model. The forces that affect the hydrodynamic model are wind conditions and heat exchange, which are assumed to be identical over the whole study area. Wind direction, speed, air temperature and relative humidity (RH) was acquired from SMHI at weather station Göteborg A (7142) (RT90: 6405400, 1272800).

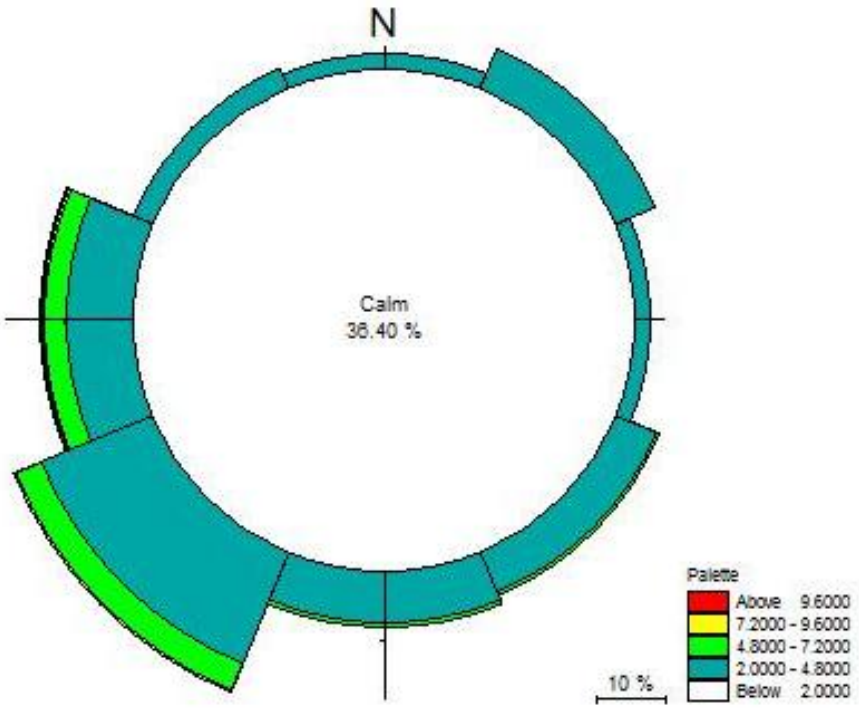

Figure 4-6: Wind rose at weather station Göteborg A (7142) from May 25th to August 17th 2011, 3 hour resolution

The wind conditions during the study period are displayed with the wind rose in Figure 4-6. The wind rose displays the wind direction as size relative to frequency and wind speed according to a colour scheme.

The air temperature, relative humidity and cloud coverage together with water temperature form up heat exchange in the model. Also defined in the heat exchange is the deviation from the standard meridian in the study area and if summer time is applicable. For this study deviation from the standard meridian was set to +1 and summer time set to +1. Cloud cover during the study period determined to be 60% as an overall average from SMHI data (SMHI, 2100c). Air temperature and relative humidity are displayed in Figure 4-7.

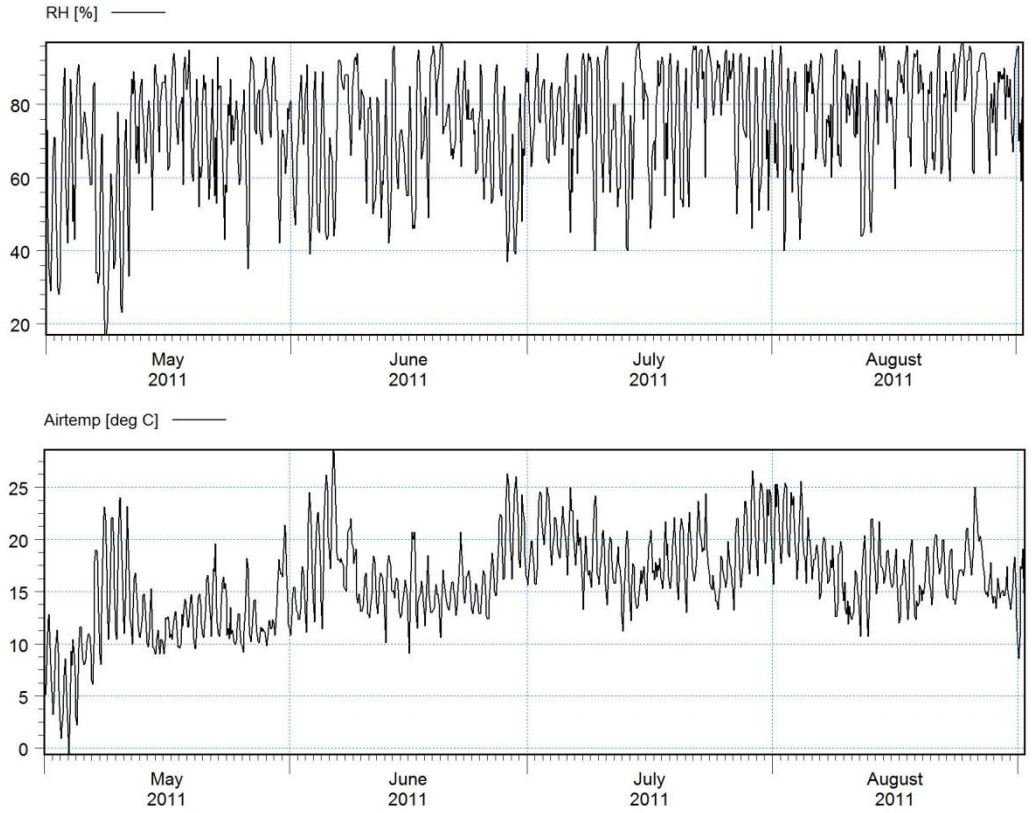

Figure 4-7: Relative humidity (RH) and air temperature at weather station Gothenburg A (7142) from May to September 2011, 3 hour resolution

Other forcing data is water temperature and salinity. Together they govern the density of the water in the model. These conditions were set to govern the water discharges into the model at boundaries Lilla Edet, Nordre Älv and Säveån and at Sources Gårdaån and Grönån (Figure 4-10). Data was acquired from Gothenburg Water Authority at Lärjeholm water intake (RT90: 6410530, 1273790). Salinity was set to 0.6 ‰. The water temperature was provided with one hour resolution and is presented in Figure 4-8 as daily mean value.

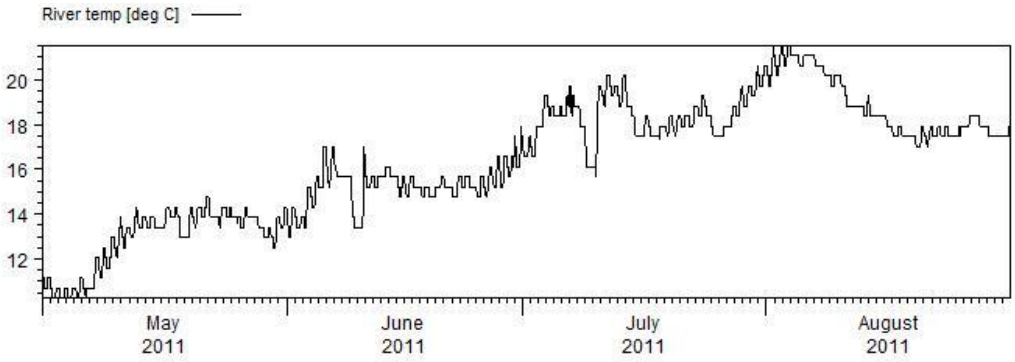

Figure 4-8: Water temperature for discharges into the model and at Nordre Älv outflow, daily resolution.

The Gothenburg harbor boundary was defined as monthly profile series, varying along 17 depths for water level and salinity as exemplified in Figure 4-9. Conditions of salinity and water temperature are extracted from SMHI CHARK database (SMHI, 2011d) at Skalkorgarna station (RT90: 6402244, 1258961) close to downstream boundary Goteborg harbor. This data provided with monthly resolution and tabulated at five levels from 0 to 13 m.

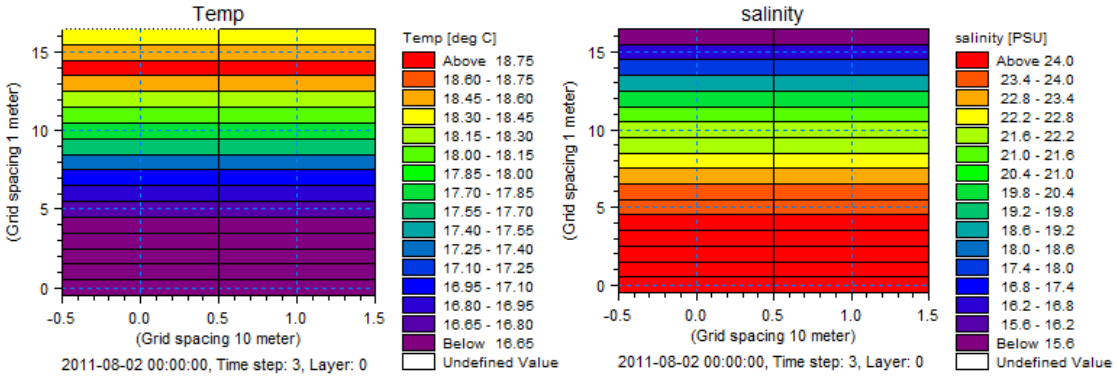

Figure 4-9: Temperature and salinity at Gothenburg harbour, monthly resolution

4.2.3 Boundary conditions

There are two types of boundaries in model, land boundary and open water boundary. Boundaries are defined in the mesh and each is associated with a code in MIKE 3. The study area consisted of four open water boundaries as Lilla Edet, Nordre Älv, Säveån and Gothenburg harbour which their positions are presented in Figure 4-10.

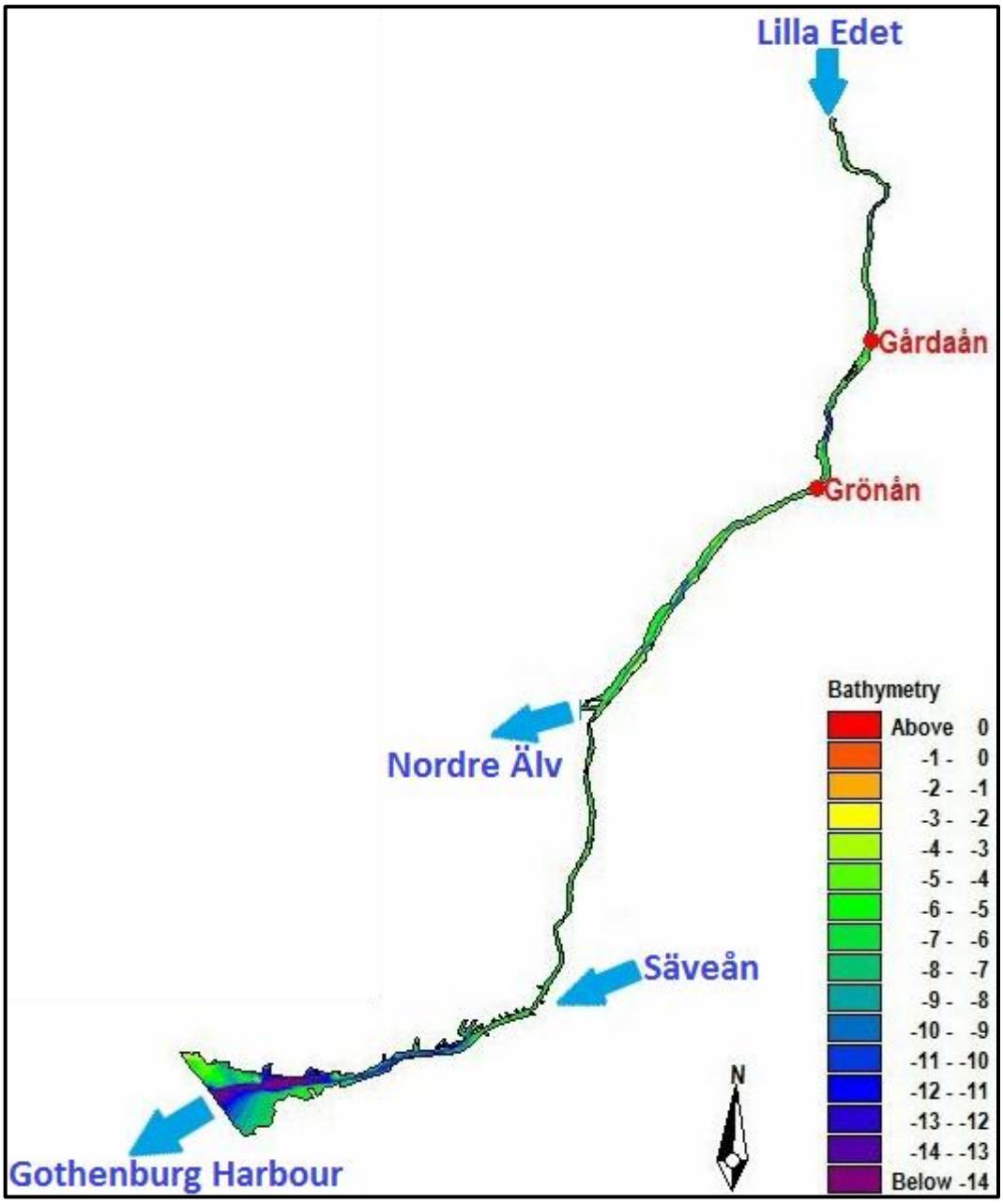

Figure 4-10: Locations of boundaries Lilla Edet, Nordre Älv, Säveån and Gothenburg harbour and the tributaries Grönån and Gårdaån (sources) in the study area.

All input data for the water boundaries were assumed to be constant along the boundary. This is due to the low variation of data obtained from measurements alongside the boundaries, which also implies that there is no need to consider spatial variation of the measurements. Thus, all input data for boundary are converted to time series files to be used in program. Boundary condition was specified as discharge time series in Lilla Edet, Norde Älv and Säveån boundaries that are displayed in Figure 4-11 to Figure 4-13.

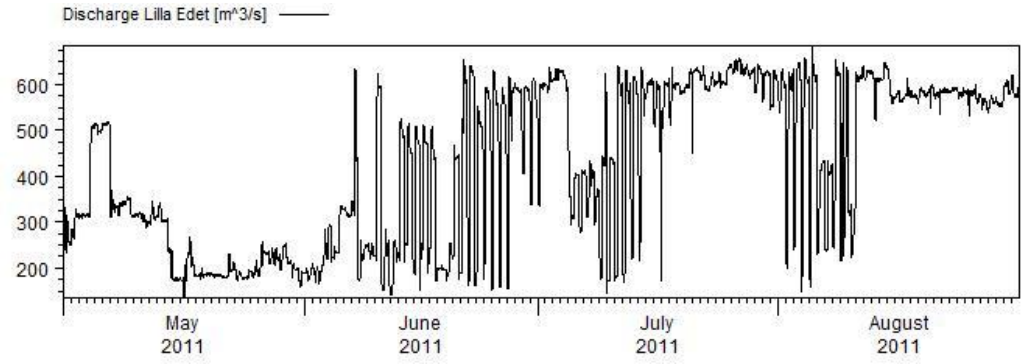

Figure 4-11: Measured discharge at Lilla Edet from May 1st to August 31st

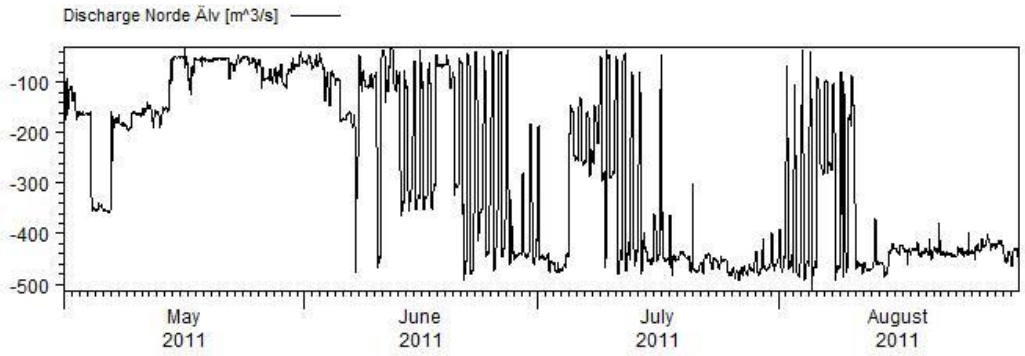

Figure 4-12: Measured discharge at Ormo in Norde Älv from May 1st to August 31st. Negative values due to outflow from model area

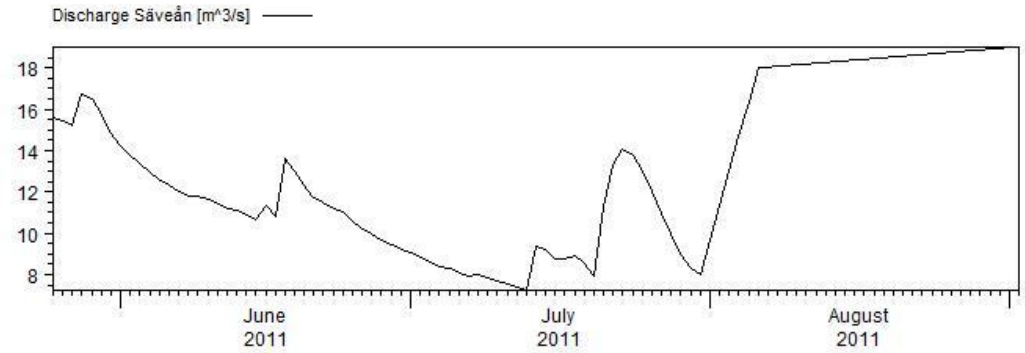

Figure 4-13: Discharge at Säveån, modelled with SMHI PULS-Model. Daily resolution until July 31st, from August 1st interpolated monthly resolution of mean flow 1990-2010

Flow data at upstream boundary Lilla Edet and Norde Älv boundary were available with hourly resolution and were provided by SMHI. However, the discharge into Göta Älv from the tributary Säveån was acquired with daily average flows until July 31st, and thereafter interpolated discharge from mean flows during 1990-2010 were used. Säveån flow data were modeled by SMHI. The data set for the water level at downstream boundary Gothenburg harbor is also provided in hourly time intervals from SMHI from Torshamnen station (RT90: 6402633, 1260601) (Figure 4-14).

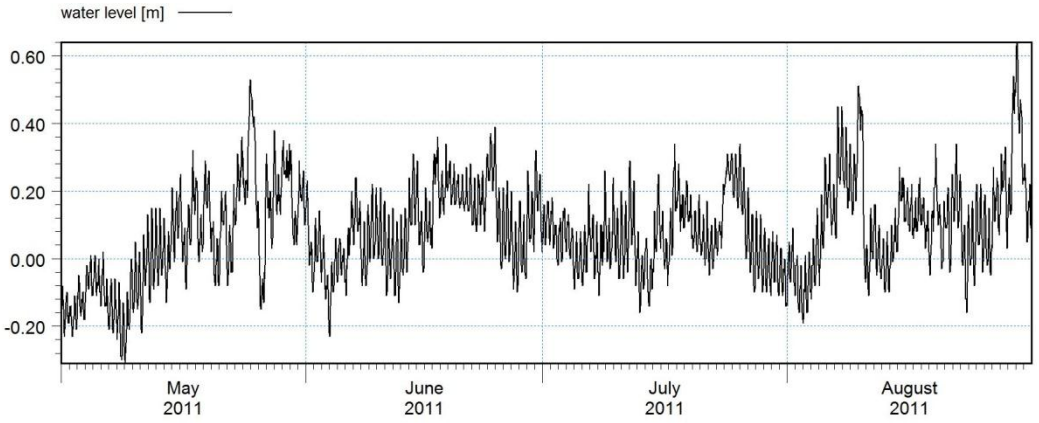

Figure 4-14: Water level at Gothenburg harbour, data acquired at Torshamnen station, height system RH2000

4.2.4 Sources

Position of the two sources, tributaries Grönån and Gårdaån, is displayed in Figure 4-10. The discharges acquired from SMHI are presented in Figure 4-15. Daily resolution from May 1st until July 31st for the tributaries and thereafter interpolated monthly mean flow from 1990-2010 was employed. Tributaries flow data were modeled by SMHI.

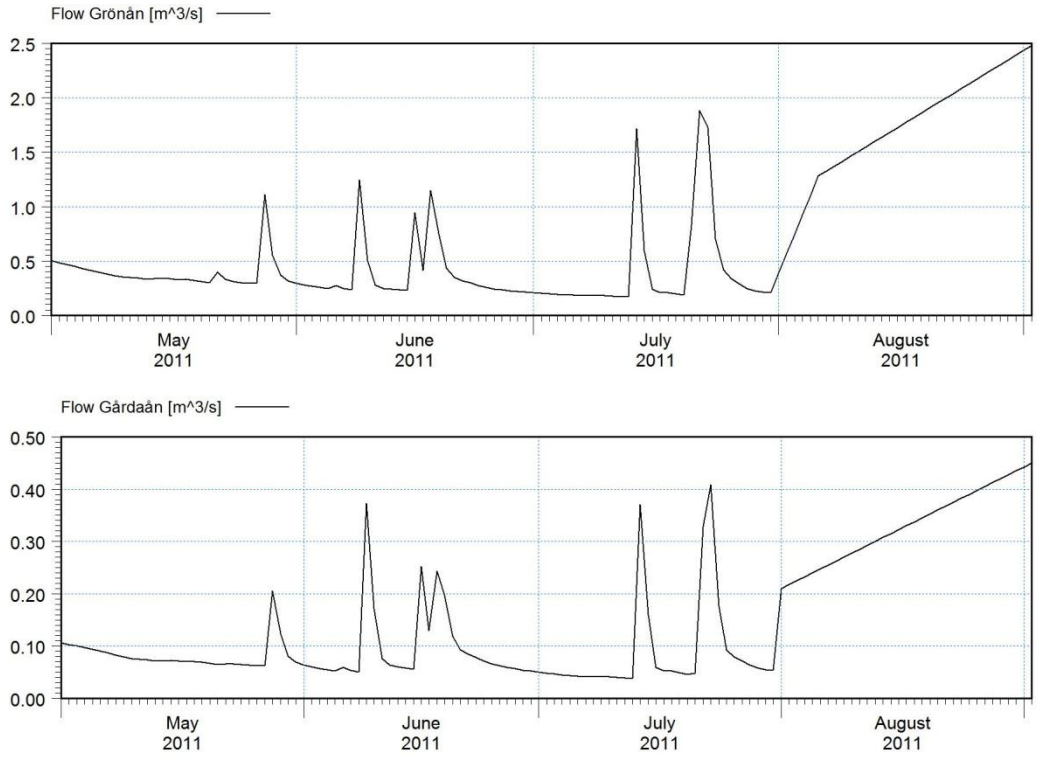

Figure 4-15: Discharges from tributaries Grönån and Gårdaån respectively during the study period

4.2.5 Comparison

Validation process is needed to check the assumptions made and investigate possible errors through the model set up which make the model results in discrepancy with the reality. As Thomann (1982) pointed out it is important to use independent data sets of

field observation for the validation process. This is due to the fact that, the model is supposed to be able to predict different environmental conditions as well as the actual condition. However in this study, only the comparison is carried out by using three methods in order to evaluate the accuracy of the results. Initial comparison was executed by comparing the water level from model simulation with measurements at Lilla Edet (RT90: 1282710, 6450720) in upstream and Götaälvbron (RT90: 1271330, 6405360). Calculated discharge at Lärjeholm (RT90: 6410530, 1273790) was then compared to field observation. Also, a comparison of measured and modeled temperature at Lärjeholm was made. Comparison locations are displayed in Figure 4-10.

4.2.6 Decoupling

Decoupling mean that a simulation of the model is made and output files for the hydrodynamic model is created. These files are later used by the microbiological model for transportation simulation of the microbes. Also decoupling enables settings for specified output files at interesting areas. For this study a 30 minute time step for the output files were selected.

4.3 Microbiological model set-up

To model the microbiological transport and decay the MIKE 3 add-on program ECO Lab was used. ECO Lab uses the result of the decoupled hydrodynamic model for transportation modelling together with a component objective method to solve decay equations. The data flow between ECO Lab and hydrodynamic flow model is displayed in Figure 4-16 (DHI, 2009d). Different decay templates were created for *Norovirus* and for the studied faecal indicators. The methodology to compose an ECO Lab template is described in ECO Lab User Guide developed by DHI (2009b).

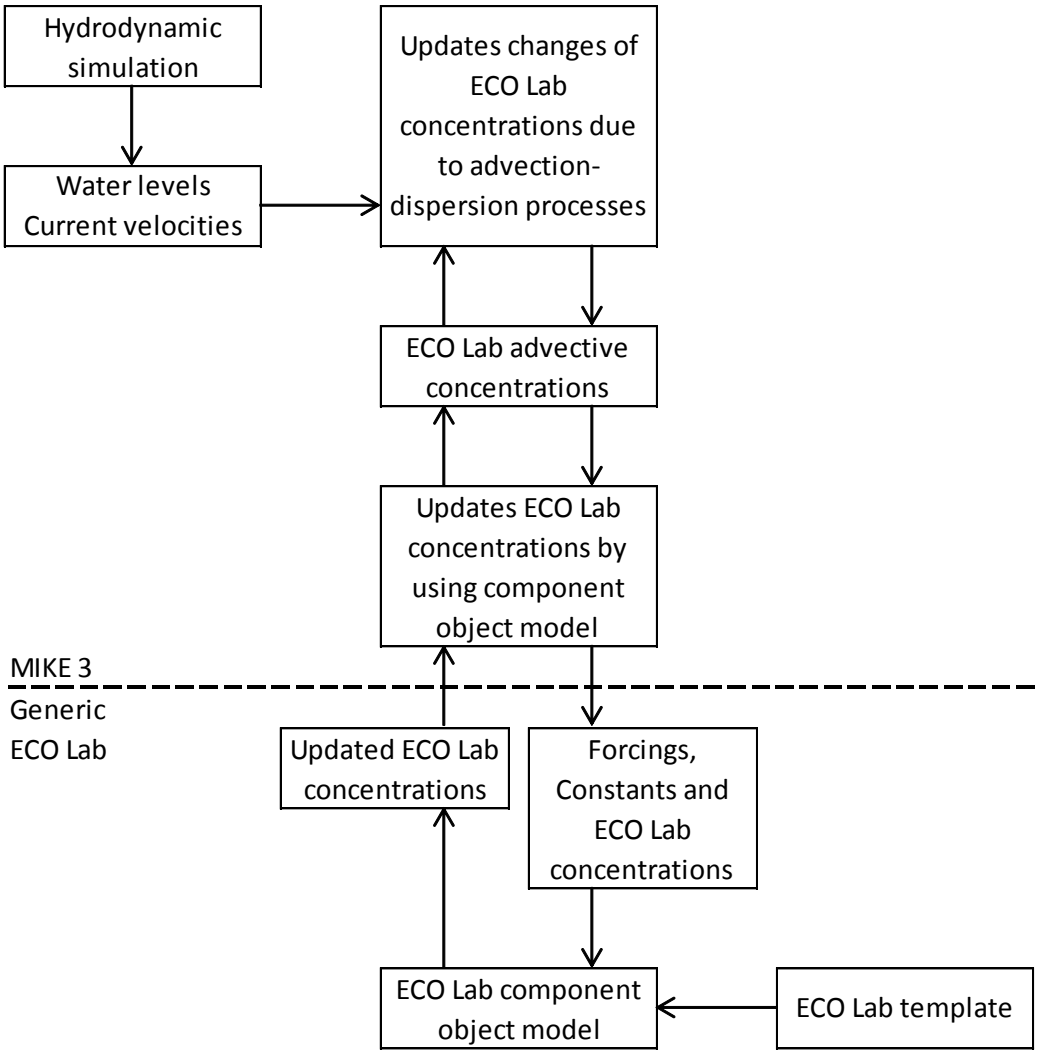

Figure 4-16: Data flow between ECO Lab and hydrodynamic flow model (modified from DHI, 2009d)

4.3.1 Input data

Since the background salinity in Göta Älv varies close to 0.6 ‰, this study follows the study by Sokolova (2011) and it was assumed that salinity is not affecting the decay of the studied microbes. The equations used to describe inactivation of faecal indicators are described in section 2.3.2. The resulting parameter θ_S in equation (8) becomes 1 and is thus neglected. The decay rates for light intensity and temperature are displayed in Table 4-4.

Table 4-4: Decay coefficients for faecal indicators in the modified Mancini model, modified from Sokolova (2011)

Faecal indicator	**Modified Mancini Model**		
	$\mathbf{k_0}$	$\mathbf{\theta_I}$	$\mathbf{\theta_T}$
E. coli	0.24	1.0	1.03
Somatic coliphages	0.22	20.0	1.08

The water temperature data is derived from the hydrodynamic model. Table 4-5 displays the monthly minimum, mean and maximum solar radiation and water

temperature for the study period. Data series for solar radiation was obtained from Gothenburg City Authority at station Skansen Lejonet (RT 90: 6405239, 1272640) due to proximity to the river and data availability. The area of interest in the study was between Lilla Edet and Lärjeholm which is relatively far from the station.

Table 4-5: Minimum, mean and maximum water temperature and hourly solar radiation for the study time period (Gothenburg City)

	Water Temperature [°C]			Hourly Solar Radiation [kW/m^2]		
Month	**Min**	**Mean**	**Max**	**Min**	**Mean**	**Max**
May	10.3	12.9	14.8	0	0.213	0.866
June	13.0	15.3	17.9	0	0.244	0.889
July	15.7	18.4	20.6	0	0.201	0.881
August	17.0	18.8	21.5	0	0.159	0.880

The Secchi depth in Göta Älv was reported to be 0.5 meter (Swedish Geotechnical Institute, 2007).

The data on levels of microbes in the water samples obtained was superimposed on the tributaries flow. Also obtained data for microbes at Lilla Edet was employed in the same way for comparison. The levels obtained from sampling and data from Lilla Edet and Lärjeholm was treated as daily data with interpolated levels in between sampling occasions and data availability. Continuous and constant loads having values of 46 (just below the detection limit) were introduced as *Norovirus* input for Lilla Edet and the two tributaries after a suggestion from Dienus (2011b). Furthermore, the boundaries Nordre Älv and Gothenburg harbour was set to zero gradient boundaries to allow for microbes to exit the model.

Furthermore, *E. coli* are introduced to the model as a single pulse input for 7 different occasions and for 3 sources, Lilla Edet, Gårdaån and Grönån, in order to understand the travel time and retention of these microorganisms along the river between Lilla Edet and Lärjeholm. The occasions were set to start on 1st of June with time intervals of 10 days and input during 24 hours. The pulse was set to 1000 CFU/100 ml.

4.3.2 Comparison

Modelled levels of microbes in the river water were compared to levels measured by Gothenburg Water Authority at stations Garn (RT90: 1283810, 6443800), Södra Nol (RT90: 1277620, 6427100) and Lärjeholm (RT90: 6410530, 1273790) for the study period (Figure 4-17). At Lärjeholm a profile of the river was set-up for investigation of the dilution of the microbes from the three different input locations. This was executed in order to validate the use of a single point at Lärjeholm for modelled time series results (Figure 5-7). If the microbes are perfectly diluted in the river, any point at the cross section is representative for the concentration at that location.

Figure 4-17: Location of the measurement stations along Göta Älv between Lilla Edet and Lärjeholm

4.4 Sensitivity analysis

The sensitivity analysis was performed on the results of microbiological model in order to evaluate the impacts from Lilla Edet, Gårdaån and Grönån at Lärjeholm, Södra Nol and Garn measurement stations. Because the comparison of the modelled and measurements were not feasible by using deterministic methods and also outcomes of microbiological model were vary significantly compare to measured data at all stations, the approach includes Monte Carlo simulation. The method is stochastic technique employs computational algorithms to calculate the results. An add-in program to Excel named Crystal Ball was used for Monto Carlo simulation to account for uncertainties and variation in results.

The simulation of the microbiological model resulted in a decoupled volume series with all concentrations interpolated for all time steps during the study period. From this decoupled model, time series were extracted at or close to the measurement locations. The resulting time series displayed the concentration of *E. coli* at the selected points with a two hour resolution over the study period, a total of 1009 time steps. Thereafter these time series were converted to distributions in Excel with Crystal Ball

4.5 Future scenario

For the future scenario investigation of a worst case scenario setting with data for the year 2100 is employed for discharges into the river, sea water level rise and air and water temperature. Table 4-6 displays the parameters affected and the expected change in the hydrodynamic model settings.

Table 4-6: Future scenario settings with respect to worst case climate change scenario for year 2100 (IPCC, 2007; SMHI, 2011e)

Location	Parameter	Change
Forcing	Air temperature	+ 4.5 °C
Lilla Edet and Nordre Älv	Discharge	+ 20 %
	Water temperature	+2.5 °C
Tributaries Gårdaån, Grönån and Säveån	Discharge	+ 20 %
	Water temperature	+2.5 °C
Gothenburg harbour	Water level	+ 40 cm
	Water temperature	+ 2.5 °C

The hydrodynamic model was simulated for the same period of time as the original hydrodynamic model and with identical other input data settings. The microbiological model is then simulated over the decoupled result with identical settings as for measurements during 2011 and with the same inactivation settings.

5 Results

5.1 Sampling results

Sampling results were acquired from four locations along Göta Älv. In addition to the sampling at Gårdaån and Grönån, the water at Lilla Edet and Lärjeholm was analysed. The result for *E. coli* is displayed in Table 5-1 and Figure 5-1.

Table 5-1: Sampling results for *E. coli* at Grönån and Gårdaån and measured levels at Lilla Edet. No data is represented by dash in the table.

***E. coli* [CFU/100ml]**			
Date	**Lilla Edet**	**Gårdaån**	**Grönån**
June 8th	70	520	760
June 22nd	70	-	-
July 6th	30	200	740
July 20th	13	-	-
Aug 3rd	30	500	75
Aug 17th	70	-	-

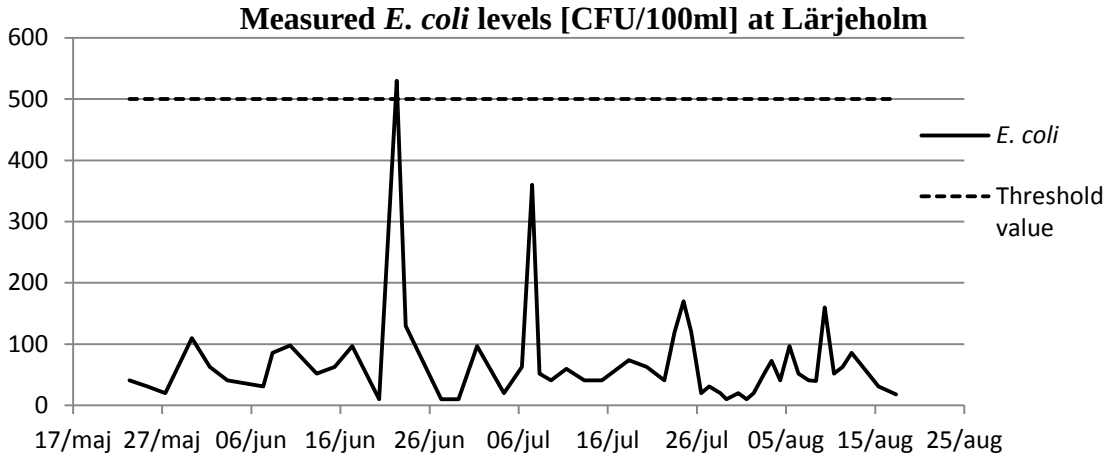

Figure 5-1: Measured levels of *E. coli* at Lärjeholm compared to threshold value of raw water (raw data obtained from Gothenburg water authority).

Sample results of somatic coliphages from Gårdaån and Grönån and obtained measurements at Lilla Edet and Lärjeholm water intake are presented in Table 5-2.

Table 5-2: Sampling results for somatic coliphages at Grönån and Gårdaån and levels at Lilla Edet and Lärjeholm

Somatic coliphages [PFU/100ml]				
Date	**Lilla Edet**	**Gårdaån**	**Grönån**	**Lärjeholm**
June 8th	25	1100	17	34
July 6th	100	<10	10	100
Aug 3rd	-	250	63	23
Aug 31st	110	-	-	150

The analysis of *Norovirus* from samples in Gårdaån and Grönån resulted in levels below detection limit at all times. Likewise, no results from Lilla Edet Figure 5-2or Lärjeholm were obtained. Since qRT-PCR has a detection limit of 47 viruses /100 ml, the levels were assumed to be 46 viruses/100 ml at all times for Lilla Edet, Grönån and Gårdaån.

5.2 Hydrodynamic modelling results

The simulated water level (RH2000) at Lilla Edet is displayed in Figure 5-3 compared to measurements during the study period.

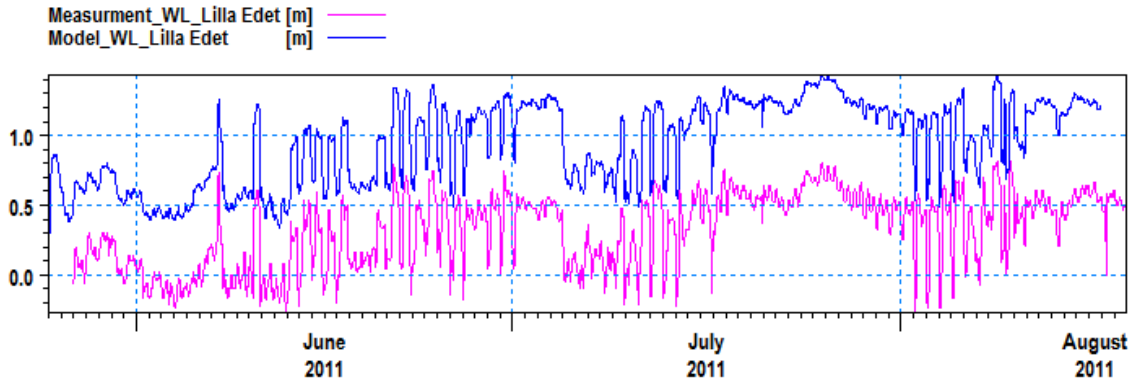

Figure 5-3: Measured and modelled water level at Lilla Edet for the study period

Water level comparison at Götaälvbron is displayed in Figure 5-4.

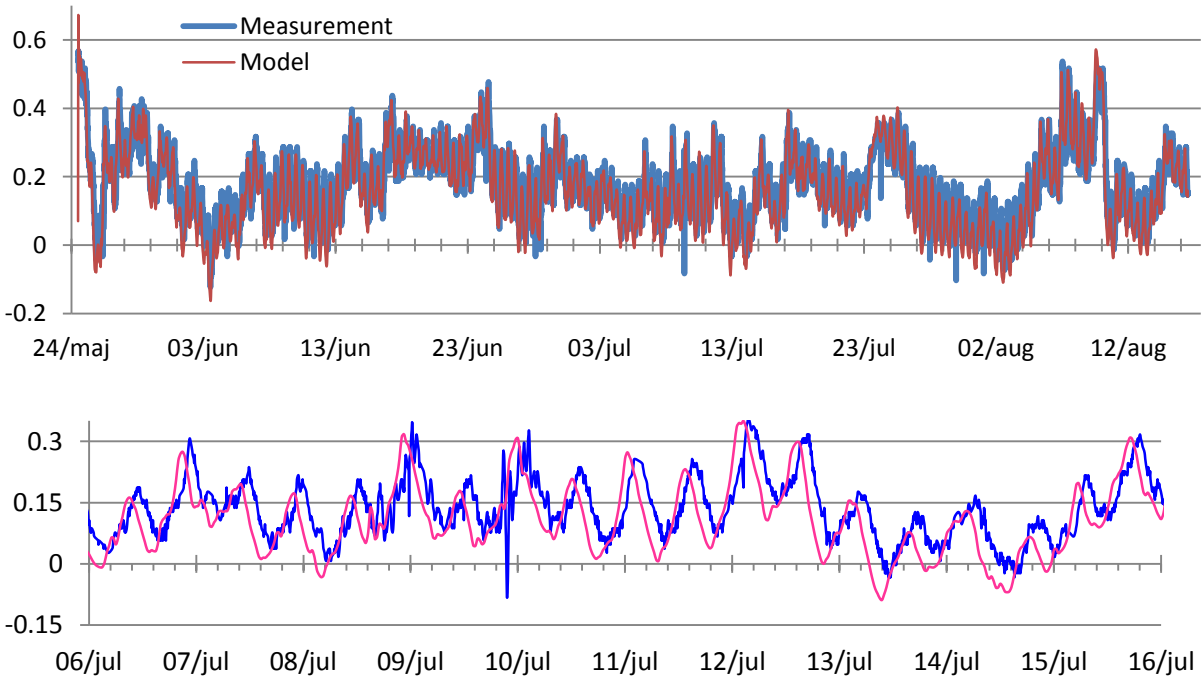

Figure 5-4: Above: Time series of measured and model water level at Götaälvbron between 25th of May to 17th of August. Below: Better resolution from 6th of July to 16th of July. Y-axis is in meters

The result in Figure 5-3 reveals that the model overestimates the surface elevation at Lilla Edet by approximately 0.5 m. However, the trend in modelled water level follows the measurements very well. At Götaälvbron, the overall surface elevation agreement between model and measurements is very good.

Figure 5-5 presents the comparison between measured discharges with daily resolution and simulation results with both hourly and daily resolution at Lärjeholm. Modelled discharge shows larger discharges about 180 m^3/s, compared to measured discharges about 150 m^3/s.

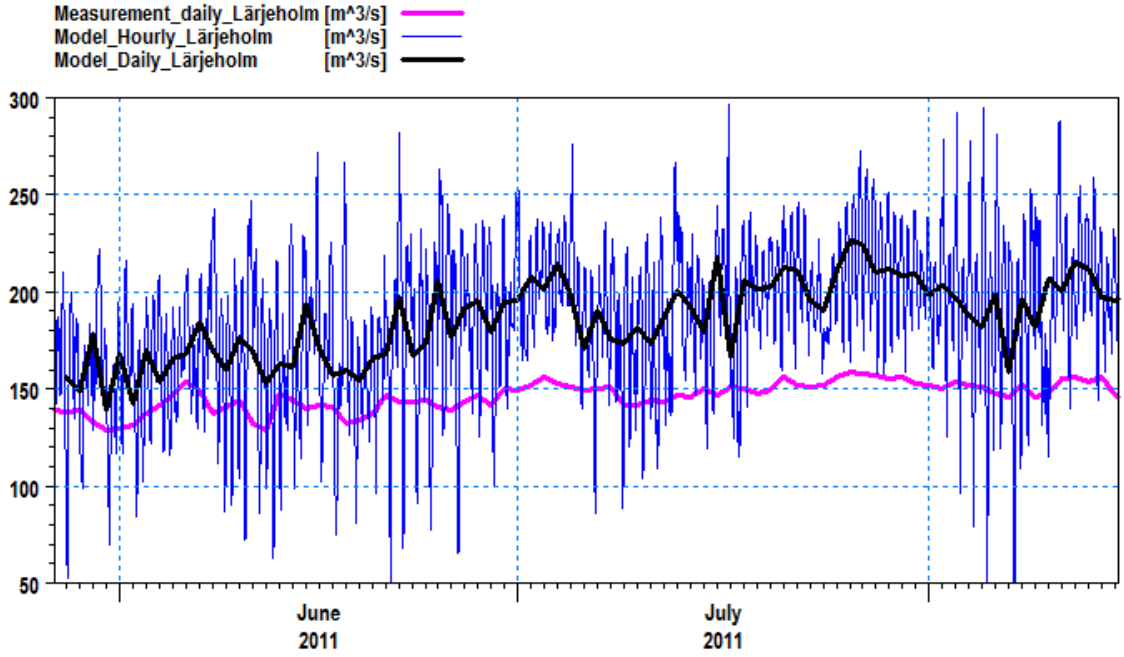

Figure 5-5: Measured and modelled flow at Lärjeholm water intake during the study period

Figure 5-6 shows the comparison of temperature measurements versus the model at Lärjeholm. With a few exceptions regarding the temporal correlation, the model simulates the temperature relatively well.

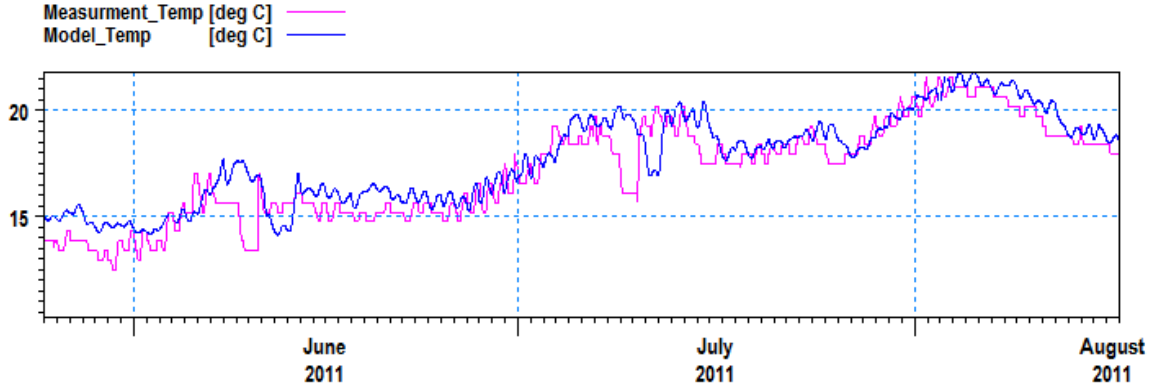

Figure 5-6: Measured and modelled temperature at Lärjeholm water intake for the study period

5.3 Microbiological modelling results

The river profile at Lärjeholm showed that the microbial levels are perfectly diluted in the water body as exemplified in Figure 5-7.

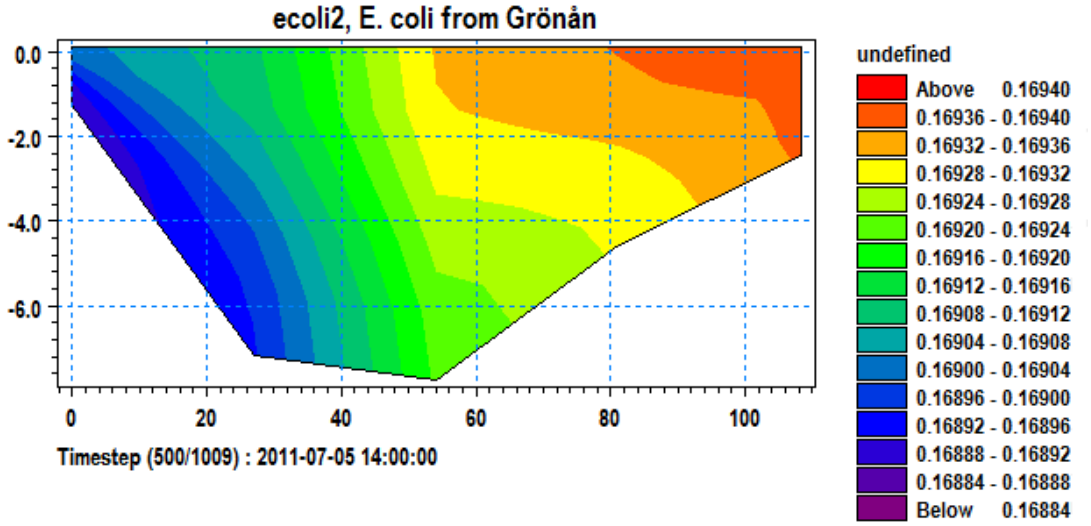

Figure 5-7: Vertical profile of *E. coli* concentration in Göta Älv (contribution from Grönån) at Lärjeholm at 14:00 on July 5th. Legend represents *E. coli* levels [CFU/100ml].

The results of the microbiological model show that *E. coli* and coliphages from Lilla Edet reach the water intake at Lärjeholm (42 km downstream) between 10 to 50 hours after release, depending on the flow velocity in the river. Concentrations are reaching up to highest value about 20 hours after the first parts of the pulse reaches Lärjeholm. Furthermore, the release from Gårdaån and Grönån takes between 4 to 36 hours respectively to get to Lärjeholm. The time series of E. coli at Lärjeholm released from Lilla Edet is exemplified in Figure 5-8.

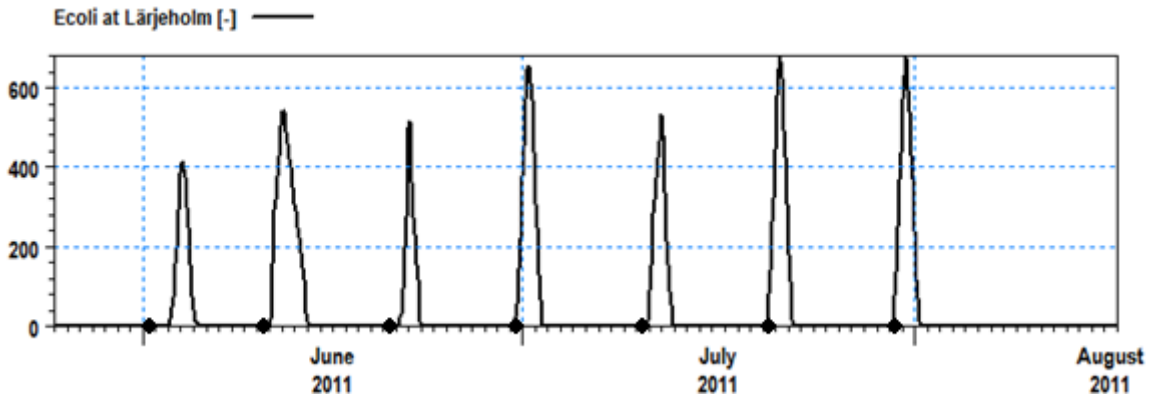

Figure 5-8: Line represents concentration [CFU/100 ml] at Lärjeholm from releases (dots) at Lilla Edet of 1000 CFU/100 ml

The concentration of *E. coli* release was set to 1000 CFU/100 ml for each release. Concentration reaching Lärjeholm after each release varied from 412 to 667 CFU/100 ml from release in Lilla Edet and from 0.052 to 0.47 CFU/100 ml for release of 1000 CFU/100 ml from Gårdaån.

The time series of *E. coli* and somatic coliphages concentrations at Lärjeholm together with released concentration from Gårdaån, Grönån and Lilla Edet are plotted in Figure 5-9.

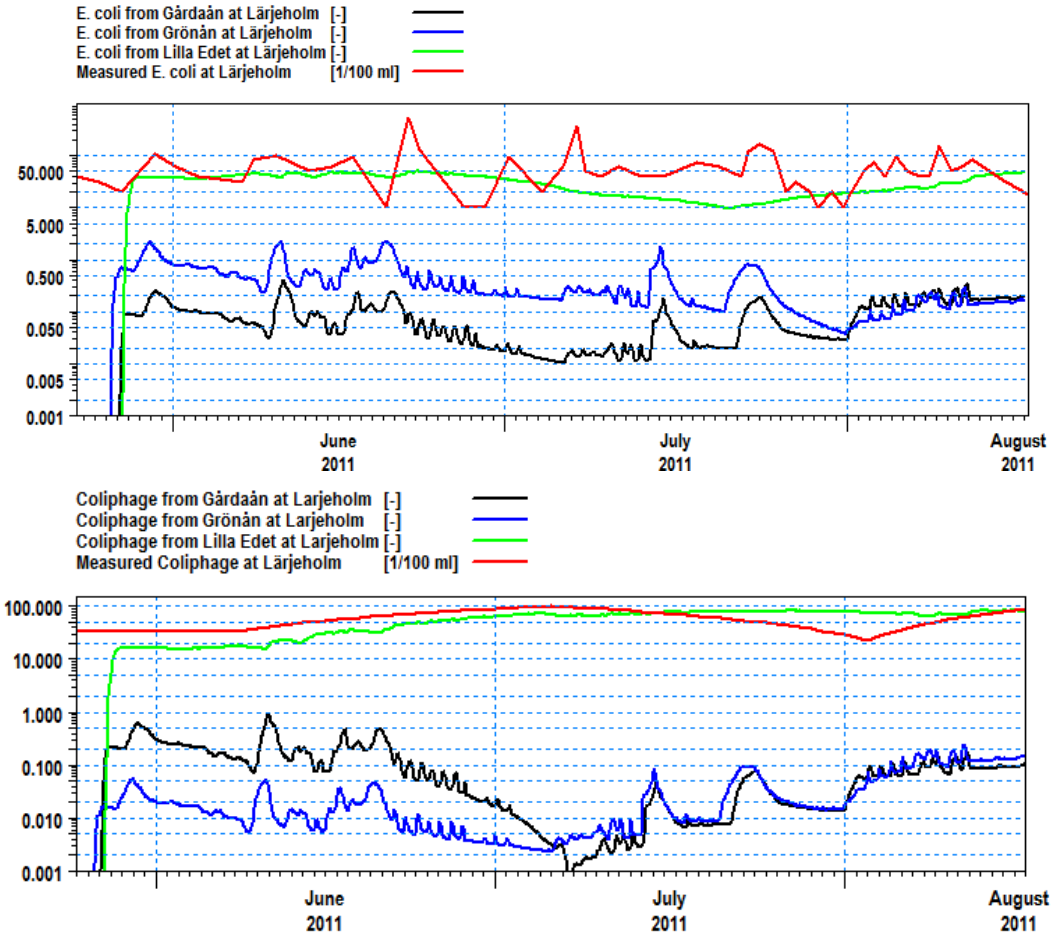

Figure 5-9: Above: Modelled levels of *E. coli*/100 ml at Lärjeholm from Gårdaån, Grönån and Lilla Edet and measured levels at Lärjeholm. Below: Results for somatic coliphages/100 ml. Lognormal y-axis

The levels of *Norovirus* reaching Lärjeholm from Lilla Edet, Grönån and Gårdaån are presented in Figure 5-10. Conservative model yields only dilution as a factor for decreased levels.

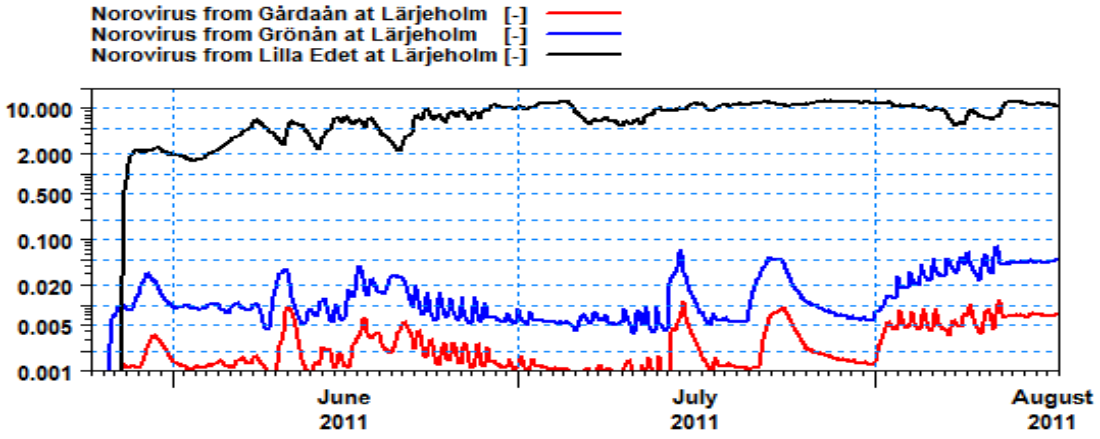

Figure 5-10: Norovirus levels at Lärjeholm from Lilla Edet, Grönån and Gårdaån from constant input levels of 46 viruses/100 ml.

Comparison of measured and modelled levels of *E. coli* at measurement stations Garn and Södra Nol is presented in Figure 5-11. Garn is located upstream of the two tributaries. The resolution of the data at Garn is measurements two to seven times a week and at Södra Nol is between six times per week to once every two weeks.

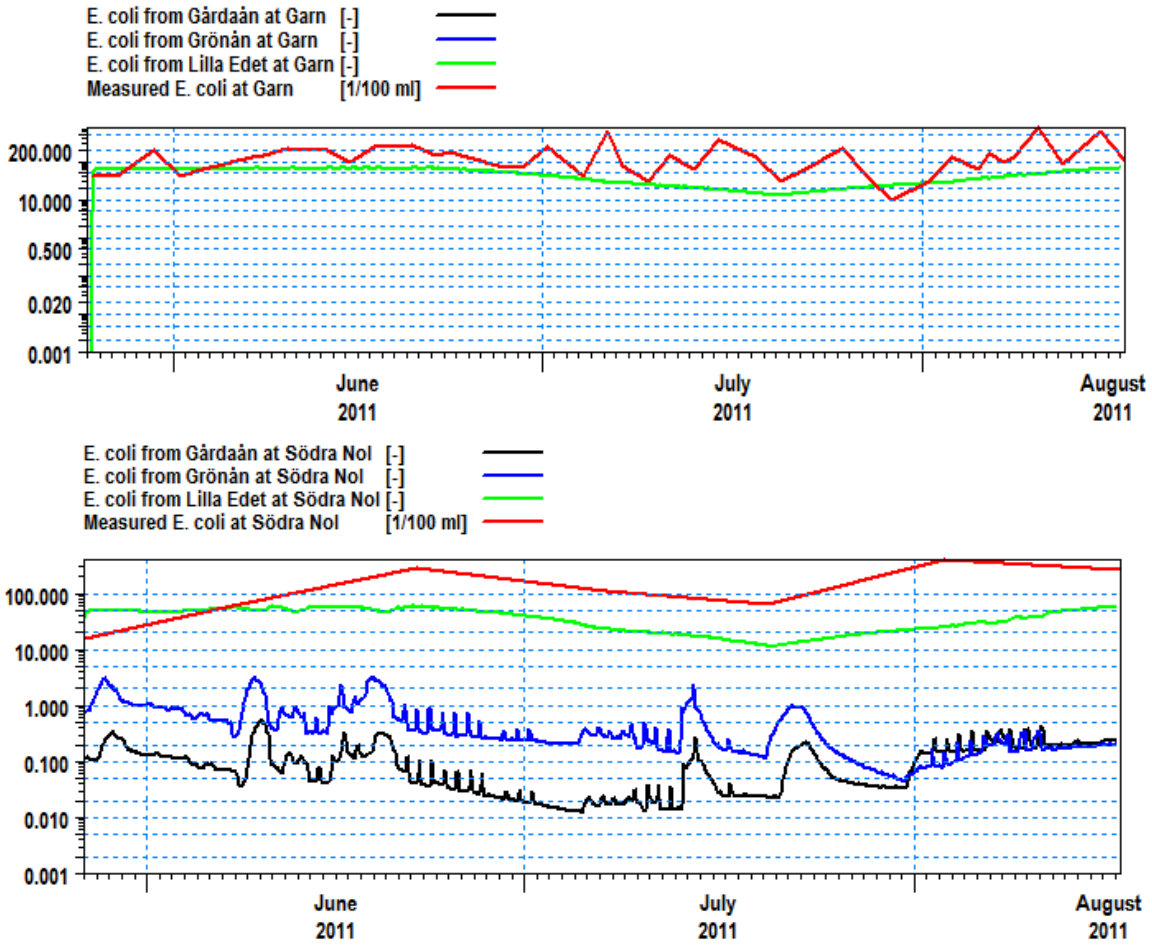

Figure 5-11: Above: Modelled levels of *E. coli* at Garn from Gårdaån, Grönån and Lilla Edet and measured levels at Garn. Below: Results for somatic coliphages. Lognormal y-axis

5.4 Sensitivity analysis

Using the approach mentioned in chapter 4.4, sensitivity analysis of modelled impacts of *E. coli* from Gårdaån, Grönån and Lilla Edet on measured levels and total modelled levels at Lärjeholm is presented in Table 5-3.

Table 5-3: Contribution of modeled *E. coli* levels [CFU/100ml] from Lilla Edet, Grönån and Gårdaån at the measurement stations from Monte-Carlo simulation of time series data. No value on 95 percentile of measurements from Södra Nol, due to insufficient number of data points.

Station	Measured		Modelled		Contribution of *E. coli* to modeled concentration		
	Mean	95 percentile	Mean	95 percentile	Lilla Edet	Gårdaån	Grönån
Garn	159.87	474.05	44.67	76.64	100%	0%	0%
Södra Nol	164.5	-	37.73	58.21	99.99%	~0%	~0%
Lärjeholm	70.2	201.11	30.38	53.73	99.5%	0.4%	0.1%

The probability that the measured data is higher than the modelled is displayed as cumulative probability in Figure 5-12. The approach is explained in Chapter 4.4.

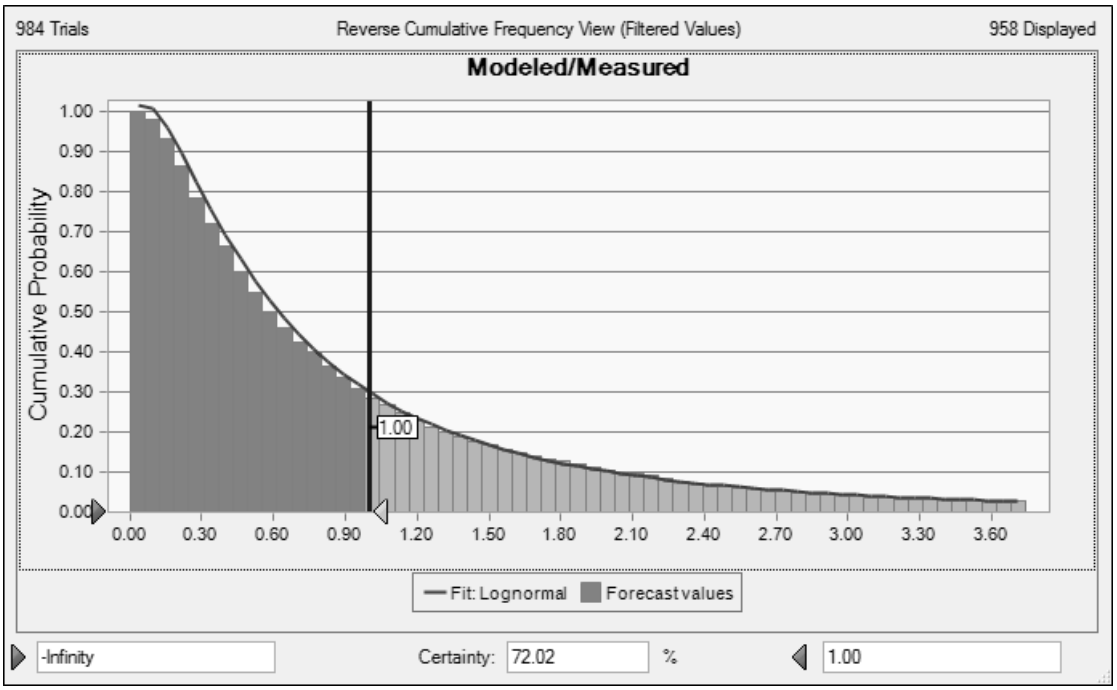

Figure 5-12: Result of Monte-Carlo simulation for investigating the certainty that the measured levels of microbes in Lärjeholm is higher than the modelled

Results of stochastic analysis revealed that the probability that the model underestimates the concentration of *E. coli* at Lärjeholm is 72 present.

Results in Table 5-3 indicate that the *E. coli* from Lilla Edet is the main contributor to rates of *E. coli* at Lärjeholm. Impacts from Lilla Edet, Gårdaån and Grönån at Lärjeholm, Södra Nol and Garn measurement stations are also presented in detail as follow:

Södra Nol

Figure 5-13 to Figure 5-15 display the resulting lognormal distributions for *E. coli* levels at Södra Nol from Gårdaån, Grönån and Lilla Edet respectively.

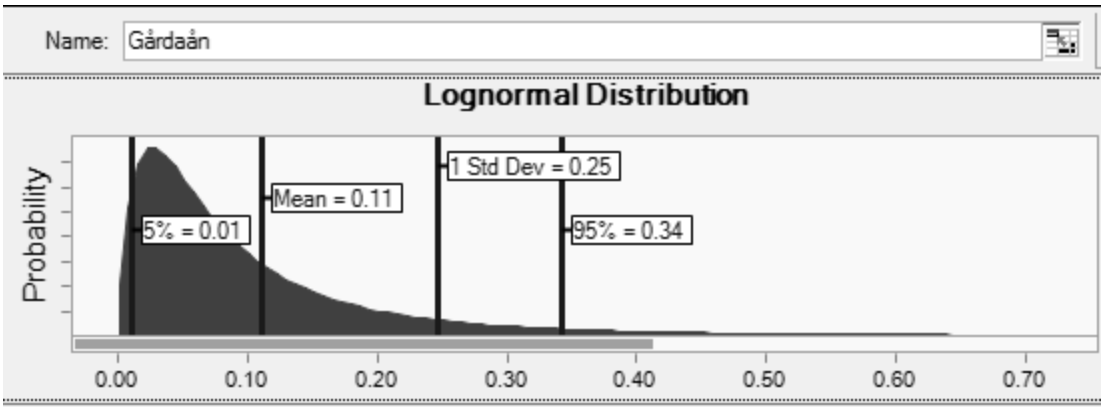

Figure 5-13: Lognormal distribution of modelled *E. coli* levels at Södra Nol from Gårdaån

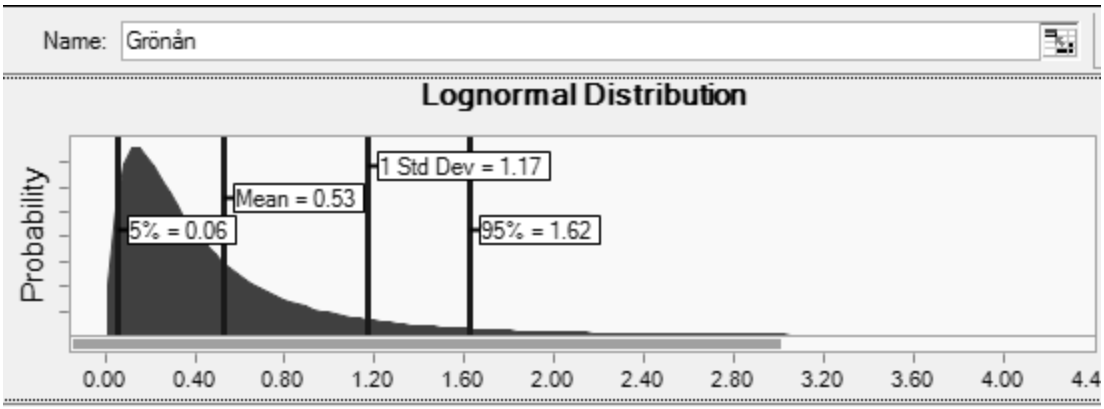

Figure 5-14: Lognormal distribution of modelled *E. coli* levels at Södra Nol from Grönån

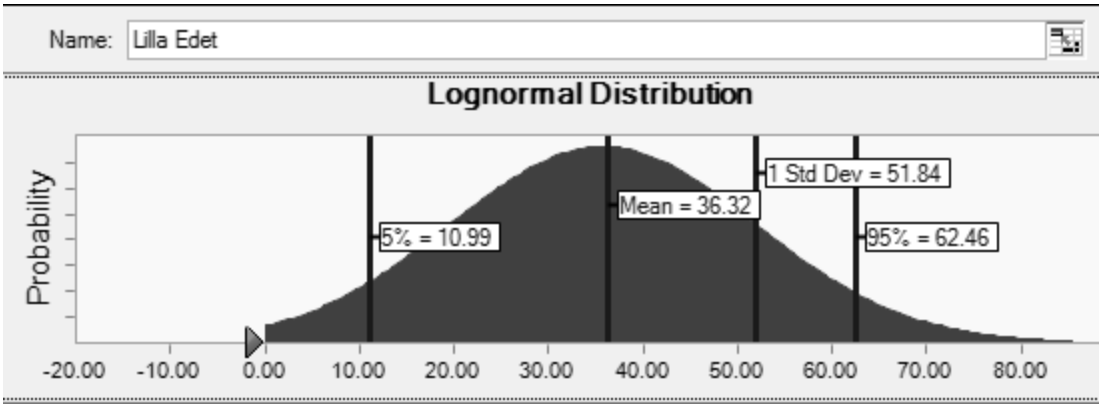

Figure 5-15: Lognormal distribution of modelled *E. coli* levels at Södra Nol from Lilla Edet

The contributing levels, in form of distributions, then were added with each other in an iterative process to form up a forecasted sum of all modelled microbial levels. The added *E. coli* distribution at Södra Nol is displayed in Figure 5-16.

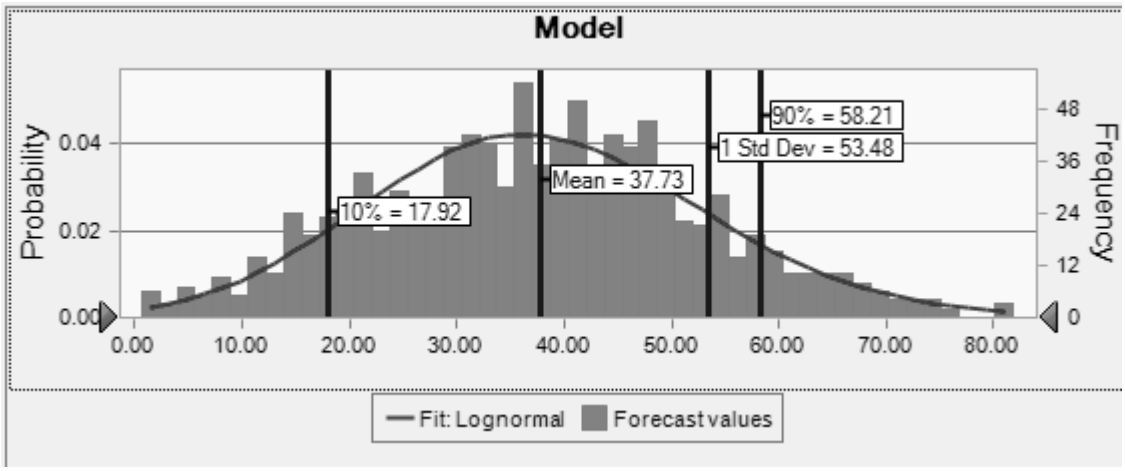

Figure 5-16: Lognormal distribution of modelled *E. coli* levels at Södra Nol from Gårdaån, Grönån and Lilla Edet combined

From the information in Figure 5-16 the sensitivity analysis is extracted as shown in Table 5-4.

Table 5-4: Sensitivity analysis of origins of modelled microbial levels at Södra Nol with contribution of variance and rank correlation information

Assumptions	Contribution to variance	Rank Correlation
Lilla Edet	0.9999	0.9991
Gårdaån	6.1599E-05	0.0078
Grönån	2.397E-05	0.0049

Södra Nol only had eight measurments, which is to low for constructing a distribution.

Garn

Since Garn only have modelled *E. coli* contribution from Lilla Edet (Figure 5-17), these levels are the lognormal distributed and compared to lognormal distribution of measured levels of *E. coli* (Figure 5-18).

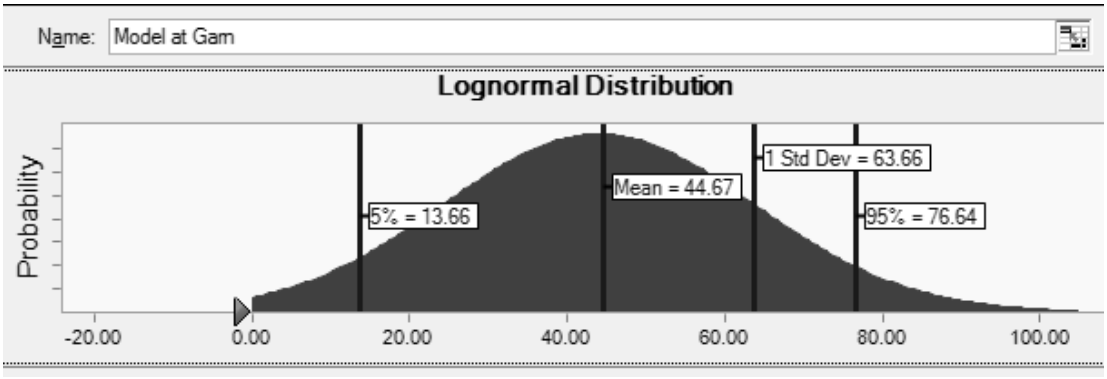

Figure 5-17: Lognormal distribution of modelled levels of *E. coli* at Garn from Lilla Edet

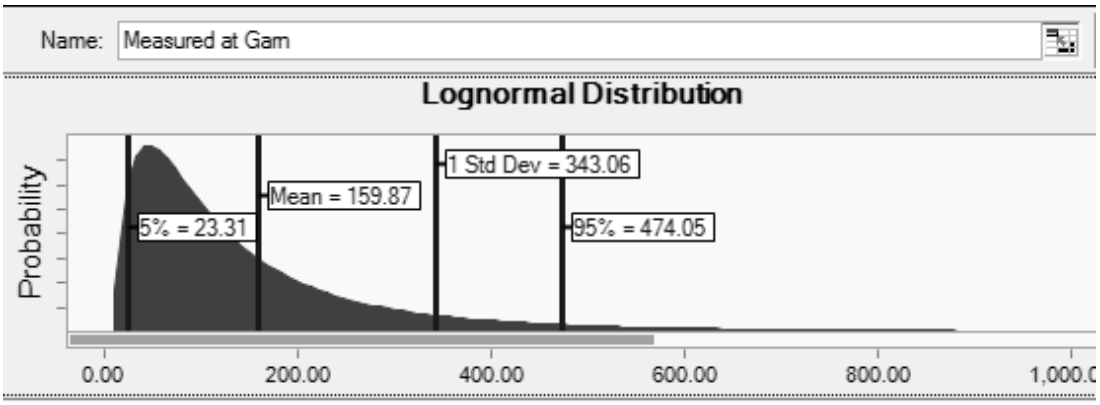

Figure 5-18: Lognormal distribution of measured levels of *E. coli* at Garn

Since Garn only have *E. coli* levels from Lilla Edet there is no need of sensitivity analysis.

Lärjeholm

Figure 5-19 to Figure 5-21 display the resulting lognormal distributions for *E. coli* levels at Södra Nol from Gårdaån, Grönån and Lilla Edet respectively.

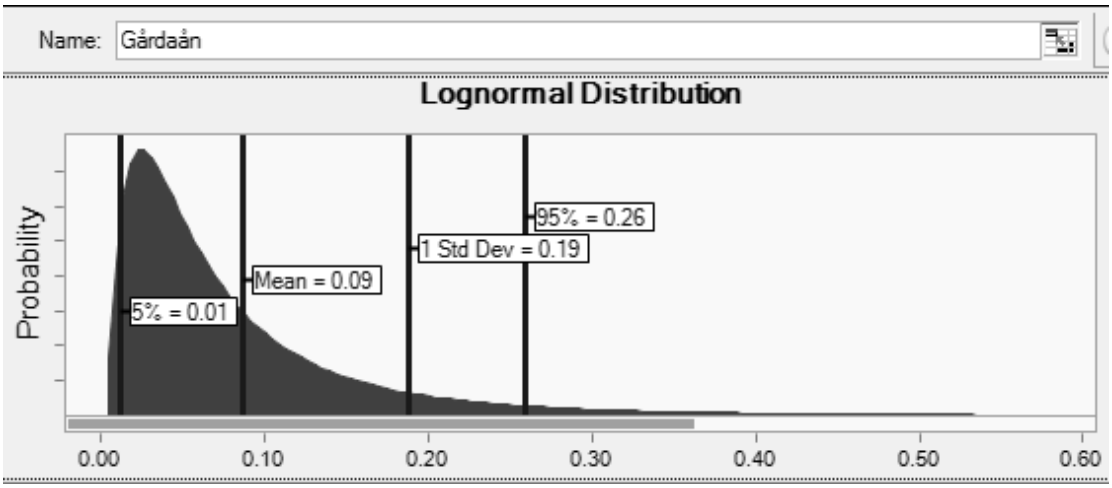

Figure 5-19: Lognormal distribution of modelled E. coli levels at Lärjeholm from Gårdaån

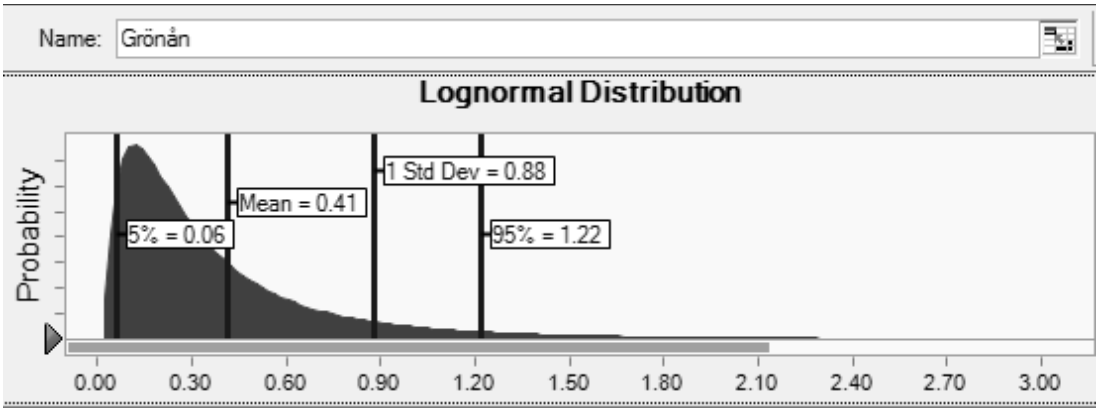

Figure 5-20: Lognormal distribution of modelled E. coli levels at Lärjeholm from Grönån

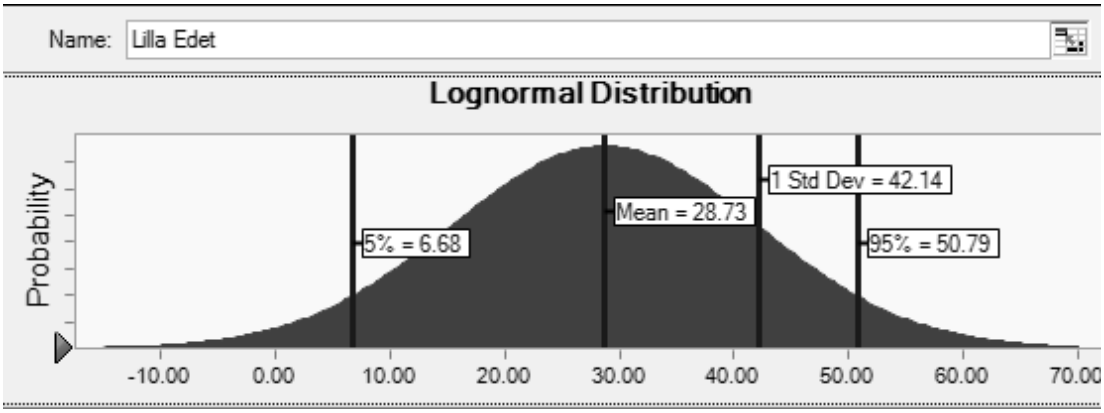

Figure 5-21: Lognormal distribution of modelled E. coli levels at Lärjeholm from Lilla Edet

The overall modelled levels of *E. coli* at Lärjeholm are displayed in Figure 5-22: Lognormal distribution of modelled E. coli levels at Lärjeholm from Gårdaån, Grönån and Lilla Edet combined.

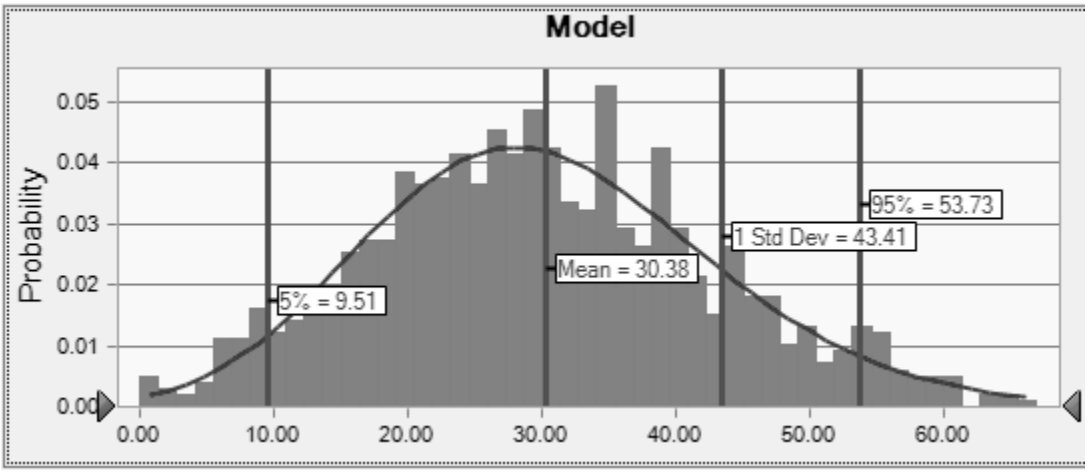

Figure 5-22: Lognormal distribution of modelled E. coli levels at Lärjeholm from Gårdaån, Grönån and Lilla Edet combined

And the sensitivity analysis for Lärjeholm is displayed in Table 5-5.

Table 5-5: Sensitivity analysis of the origins of modelled microbial levels at Lärjeholm with contribution of variance and rank correlation information

Assumptions	Contribution to variance	Rank Correlation
Lilla Edet	0.9953	0.9995
Gårdaån	0.0038	0.0621
Grönån	0.0008	0.0288

In order to further investigate the situation at Lärjeholm regarding levels of *E. coli*, the certainty that the measured concentration is higher than the modelled is obtained simply by dividing the modelled distribution with the measured distribution (Figure 5-23). The forecasted outcome is presented in Figure 5-12.

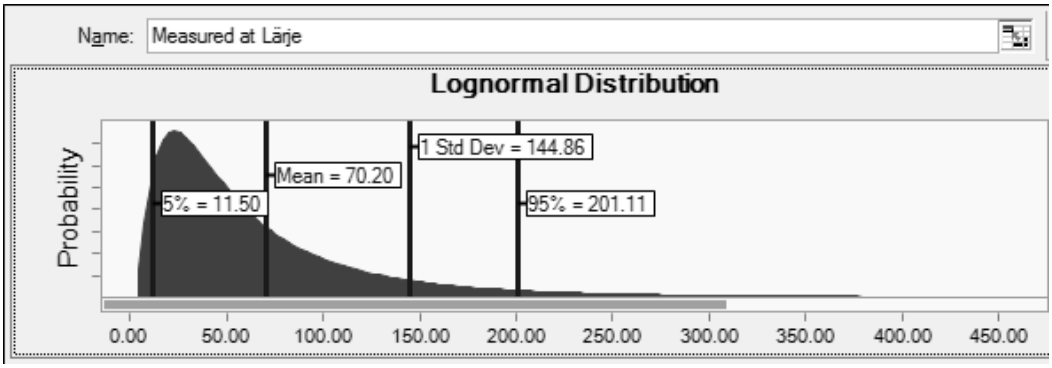

Figure 5-23: Lognormal distribution of measured levels of *E. coli* at Lärjeholm

5.5 Future scenario results

The discharge at Lärjeholm for future scenario settings is presented in Figure 5-24.

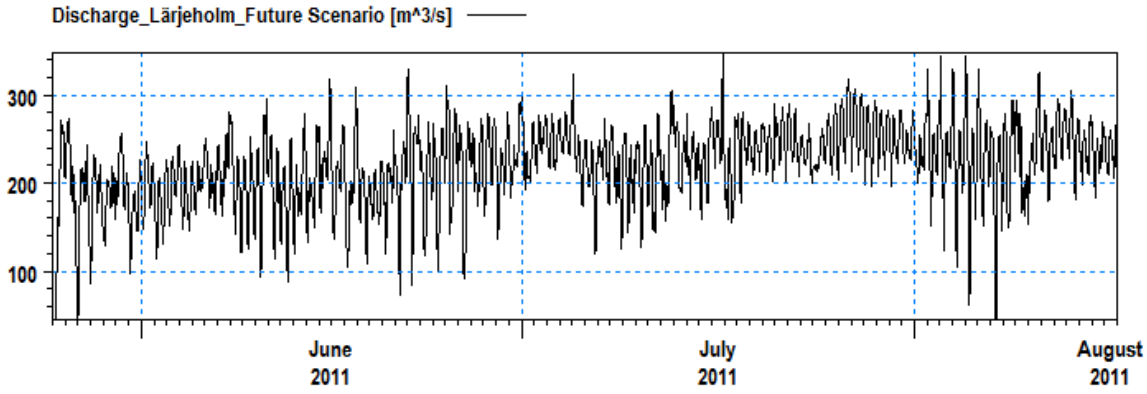

Figure 5-24: Modelled flow at Lärjeholm with future scenario temperature, flow and water level settings.

The average discharge will increase by 45 m^3/s in Lärjeholm. Figure 5-25 shows the water level variation at Götaälvbron for future scenario settings. The average water level will increase from 0.16 to 0.67 m at Götaälvbron.

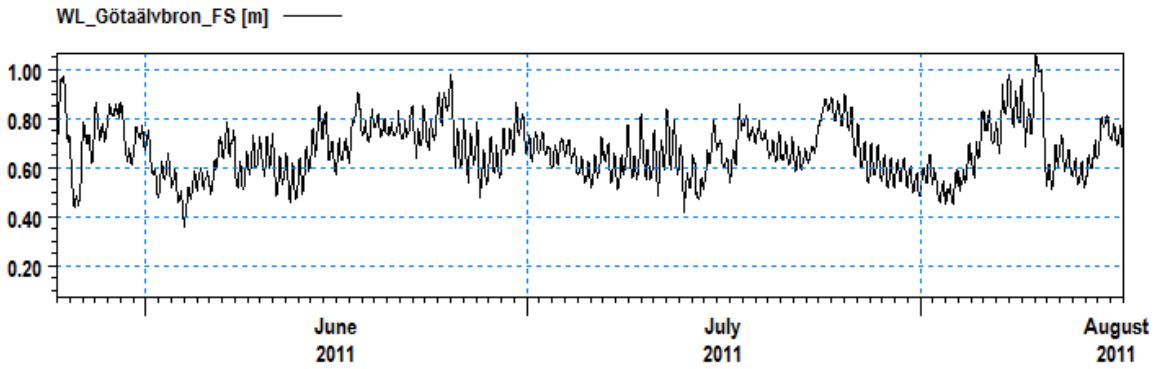

Figure 5-25: Modelled water level at Götaälvbron with future scenario temperature, flow and water level settings.

The resulting levels of *E.coli* at Lärjeholm from Grönån, Gårdaån and Lilla Edet from model simulations of future scenario are presented in Figure 5-26.

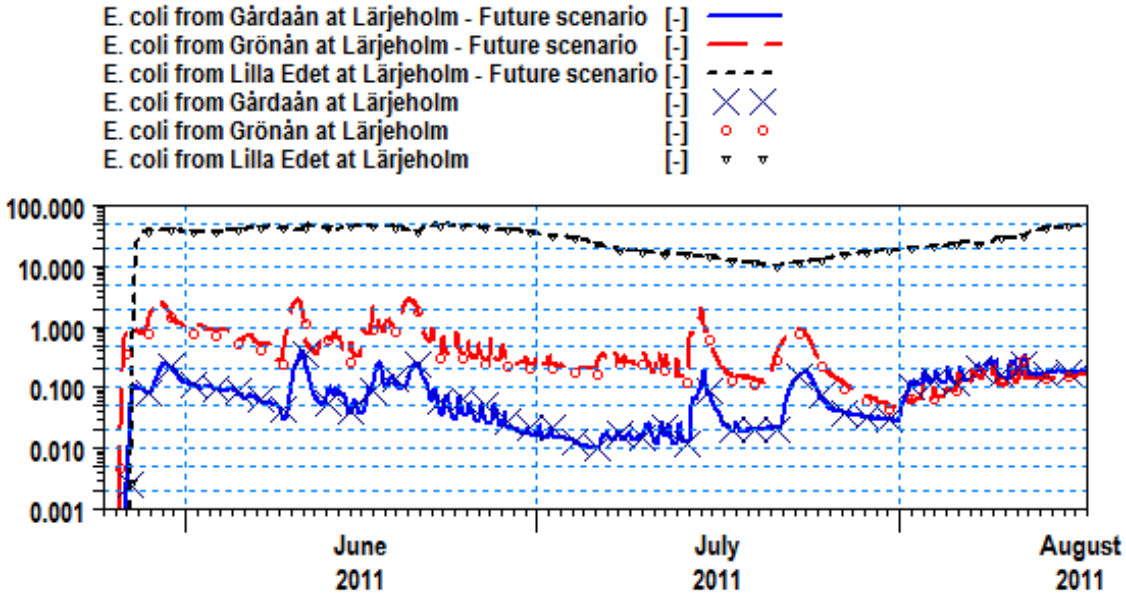

Figure 5-26. Comparison of modelled levels of *E. coli* at Lärjeholm.

Levels of *E. coli* at Lärjeholm from the tributaries and Lilla Edet are equivalent for the future scenario settings as the results from the study period 2011. The same is also true for both somatic coliphages and *Norovirus*.

6 Discussion and summary

The aim of this study was primarily to investigate the contribution of *Norovirus*, somatic coliphages and *E. coli* from tributaries Grönån and Gårdaån to the raw water intake at Lärjeholm. For *E. coli* and somatic coliphages the result was considered as satisfactory in terms of plausibility considering inactivation and transportation. For impact analysis of the two tributaries the results are considered as probable. The lower flows from the tributaries, compared to the flow in Göta Älv, and the complete dilution result in negligible impact levels at Lärjeholm from the tributaries. However, the lack of *Norovirus* data resulted in a dissatisfactory investigation where only a conservative model was used and a general discussion of inactivation of *Norovirus* was executed. The use of *E. coli* and somatic coliphages as indicators for *Norovirus* is thus not investigated. The future scenario in a risk perspective is not investigated to a great extent. Increased discharges in the future and higher water temperature are not expected to render any big changes of microbial levels at Lärjeholm. More plausible is that changes will originate from increased input levels to the river from SCOs and SSOs overflow and surface run-off.

Results

Sampling results from tributaries and obtained microbial levels at Lärjeholm and Lilla Edet show higher *E. coli* in tributaries than Lilla Edet. Gårdaån, with a WWTP upstream, show lower levels of *E. coli* than Grönån, except for the last sample occasion. This result would need to be investigated in respect to release patterns and overflow occasions at the treatment plant. For somatic coliphages, the one analysis result that stood out was in Gårdaån at June 8th. In general, Gårdaån show higher levels of somatic coliphages than Grönån which could indicate larger anthropogenic influences. In addition, the assumption made for maximum levels of *Norovirus* was taken in order to investigate the worst case scenario. The fact that the analysis results were below detection limit hampered the study, since no correlation to indicators could be investigated.

Hydrodynamic model

Having initial condition of a uniform water level of 0.07 m above the reference level the model takes three days to stabilise, which is often called warm up period. Hydrodynamic simulation showed that the flow and the hydrodynamic behaviour are mainly governed by discharge from Lilla Edet and wind. The water level comparisons show good correlation with trends both at Lilla Edet and the bridge over Göta Älv (Götaälvbron). The difference between the measurements and model water level at Lilla Edet may be due to different reference systems used in bathymetry and water level data. In addition, the measurement location in Lilla Edet for making the comparison is unknown, allowing for differences in the comparison. The overall disagreement between simulated and measured discharge at Lärjeholm is considered unreasonable. Discrepancies of more than 15 % indicate that a further detailed analysis is desirable in this respect. One reason could be that the outflow from the model at Nordre Älv is underestimated in the obtained data. No further investigation in this respect was executed and the accuracy of the flow measurement in Nordre Älv is unknown. This also indicates a higher than actual water velocity in the model. The water level comparison at Götaälvbron showed very good agreement between modelled and measurements.

It was found that the model did not produce satisfactory discharges and velocity along the river especially in downstream close to Lärjeholm. The velocity is mainly influenced by bottom roughness, boundary conditions and river slope. Since the boundary conditions are represented as measurements and with fairly good accuracy, further detailed analysis for slope and bottom roughness is necessary to analyse this aspect. For example, usually a higher roughness coefficient can be assigned in order to avoid the discharge overestimation. The use of measured temperature at Lärjeholm for input at all discharge inputs yielded a good agreement at Lärjeholm.

More broadly, the results from the hydrodynamic model indicate that the model needs to be calibrated in future work with independent sets of data in order to get the better agreement between measurements and modelled results.

Microbial model

The modelled microbial levels of *E. coli* and somatic coliphages both are at times higher than measured values at Lärjeholm. This, together with the fact that there were few results from sampling and obtained data for coliphages, means that the most sensitive parameter for this model is the input data frequency. Using monthly data or, as in the case of somatic coliphages longer intervals, is not appropriate for the model. The daily fluctuating discharge from Lilla Edet governs a large part of the impact concentrations. Therefore, a shorter measurement interval could have improved the results. In this respect, the discussion forthcoming will assume that the input data used is representing the real microbial levels.

Microbial levels at Garn and Södra Nol further suggest that the problem with higher modelled levels at Lärjeholm is to a certain extent the result of the input data at Lilla Edet. However, the less frequent measurements yield better fit than the more frequent at Lärjeholm, suggesting that the important factor could be the better agreement between the sampling and measurement inputs which can also reduce the uncertainties correlating with input data.

Vertically well-mixed layer of microbes at Lärjeholm, indicates that the simulated levels at one point represent the location well. The travel time and duration test with the "pulse" inputs showed that a pulse release during 24 hours will result in elevated microbe levels at Lärjeholm for approximately 48 to 72 hours. The pulse will reach Lärjeholm from Lilla Edet after 10 to 50 hours. This demonstrates the importance of a functioning warning system for closure of the raw water intake.

The combined simulated microbial levels at Lärjeholm were at times higher than the measured, implying that the inactivation formulation for both *E. coli* and somatic coliphages might be too conservative. Either a result of the use of a microcosm experiment for inactivation data not confirmed to be valid in river Göta Älv, or that the retention time in the river according to the model is shorter than the retention time in reality. Since water level comparison at Götaälvbron suggests inaccuracy of travel time of approximately four hours, the inactivation formulation should be revised.

Within the study area several CSOs and SSOs are located, but not included in the model. No information from CSOs and SSOs yields a gap in the result, labelled as other sources. The result is that errors in the modelled results cannot be discerned from input microbial levels from sources not investigated. Also information on the non-point sources, e.g. cattle grazing land in connection to the river and tributaries, on-site sewer systems and surface runoff, was not investigated. Therefore the origins of the microbes are unclear. If considered, the other sources could imply even higher

modelled microbe levels than the present result. In this respect, more accurate modelled river discharge from hydrodynamic model would help to narrow down the issue in order to evaluate the inactivation model for different microbes.

The microbial levels at the water intake in Lärjeholm from the tributaries compared to the impact from Lilla Edet show unambiguously small impacts. As for the modelled concentrations of *E. coli* at Lärjeholm; at no time were the mean contribution of *E. coli* from Lilla Edet below 99.5% and the contribution from Grönån and Gårdaån was 0.4% and 0.1% respectively. When compared with that the average modelled total levels of *E. coli* at Lärjeholm was about 43% of the measured mean level, the contribution from the tributaries can be said to be negligible. This result also implies that about 60% of the sources are not included in the model and that they are located between Lilla Edet and Lärjeholm. Further, the impact levels at measurement stations Garn and Södra Nol are turned out to be lower at 28% and 23% respectively. There was no discernible reason found for the discrepancies between the ratio of modelled and measured levels to be higher upstream of Lärjeholm, except for bad temporal correlation with measured and modelled data.

From transportation only the levels of *norovirus* at Lärjeholm from Grönån and Gårdaån decrease in concentration by a factor between $3\log_{10}$ to $5\log_{10}$. This is in respect to that there is no knowledge about how large amount of the input levels of 46 viruses/100 ml water that is active from the start. We assume that all are. In addition to the dilution there are inactivation parameters to consider. Since the river temperature did not exceed 25°C, temperature might not have major influence on the inactivation, if we assume that *Norovirus* behaves as FeCV or CaCV. UV-B irradiation however seem to account for a greater effect on the virus RNA. However, the Secchi depth in the river is only 0.5 meters so only the *Noroviruses* in surface level would be affected. Turbulence in the river could mix the microbes around, but no study on the turbulence has been performed. In all, at the worst case about 1 ‰ of the *Norovirus* levels from Grönån reaches Lärjeholm and 0.1 ‰ of the levels from Gårdaån. Even not considering the drinking water treatment steps, there is not much left. In contrast, the virus levels from Lilla Edet are still high, about 22 % of the input levels. Focus on *norovirus* levels at Lilla Edet is therefore recommended.

Future scenario

The levels of microbes at Lärjeholm from the two tributaries and from Lilla Edet were the same for the future scenario settings as for the study period during 2011. Higher discharge should result in higher current velocity and thereby shorter retention time in the river. This seems to have been countered almost perfectly by the higher water temperature. Another explanation is that the travel times are more or less equivalent, and inactivation from water temperature is only slightly contributing with inactivation.

Uncertainties and limitations

This study is performed during the late spring and summer 2011, which yields several constrictions to the results. During this period lower amounts of precipitation than during autumn and winter is expected. Also large amounts of surface runoff from snow melt were not considered. The advantage with this is that it is more straight forward to construct and analyse the model when fewer CSO and SSO overflow occurs to disturb the background levels of microbes. The sampled levels of microbes in the tributaries should mirror the natural levels derived from non-point sources. On the other hand, an occasion with higher surface run-off would have been required to

obtain microbe levels during extreme weather events. Furthermore, during the study period the temperatures and solar radiation intensity is at the yearly highest. Winter or early spring conditions would have provided results for inactivation during this period. It can be assumed that higher rates of microbes will survive to reach the water intake during the winter half of the year.

Also, the condition to perform this study over such recent time resulted in some gaps in the data regarding several parameters. Data accessibility increases greatly with time and both hydrodynamic and microbiological models with data from one year back are recommended for similar studies.

The sampling was performed at three occasions with four weeks interval during early June, July and August. Obviously results from a few occasions do not represent the situation well and will constrict the conclusions that can be drawn from the information. To provide a more comprehensive understanding of the behaviour of the tributaries catchment areas, more frequent or longer period of sampling would have been desired. Most probably the performed study does not investigate all relevant conditions that can occur in the area. Additionally, the low number of samples makes it impossible to correlate microbe levels with each other or to relate them with any certainty with weather events.

The sample on July 6th in Gårdaån was 9 litres of grab sample mixed with 1 litre multiplex sample. In retrospect, an all grab sample would have been preferred to provide information of the levels of microbes in the river. Furthermore, the use of PVC bottles could result in disturbance to the sample due to microbes reacting with the plastic. The analysis method for detecting *Norovirus* is also a concern. The measured levels contain booth active and inactive viruses and no distinction are possible.

Literature provides lots of studies on *E. coli*, somatic coliphages and *Norovirus*. Therefore a selection of the data used in this study was made. Relevant information on *E. coli* and somatic coliphages was generally basic knowledge and due to data from microcosm experiment (Sokolova, 2011), no inactivation data was needed. *E. coli* and somatic coliphages both are extensively investigated and different sources provide equivalent information. Same as for *E. coli* and coliphages, there are many studies on *Norovirus*; however, discussions about human Noroviruses were not considered as they are not cultivable. The sources used were the ones that were considered as best anchored in scientific documentation but they have not been conducted recently. Research on *Norovirus* has in recent years progressed and the assumption that data on FeCV and CaCV are most suitable for inactivation of *Norovirus* might be incorrect (Duizer et al., 2004). Difficulties regarding site-specific conditions are also constricting the assumptions made for inactivation.

Further, inactivation data from microcosm experiment for the indicator organisms was gathered from experiments on raw water from a lake in Gothenburg. The salinity levels should therefore be in the same range during the microcosm as measured in the river (fresh water with background salinity). Furthermore, the choice to exclude salinity as an inactivation parameter could be argued to say that the background salinity was considered in the reference microcosm experiment. The validity of the microcosm experiment results for the river conditions is however not certain and a new microcosm study should be performed for a water quality model.

Model set-up

Several data sets used in the set-up of the hydrodynamic model are not ideal. The choice to use weather data from only one location over the whole area is motivated with small differences in temperature but not for wind conditions. Wind conditions are greatly affecting the behaviour of the river and a near 50 km area adds up possible errors in the modelled results. The monthly data at the boundary Gothenburg harbour on temperature represents a problem in respect to rapid changes in temperature during spring and autumn. Before new input data occasion at Gothenburg harbour the difference between the hourly data on river temperature and the monthly can be considerable. Therefore, the data on temperature and salinity from Gothenburg harbour would be preferred with finer resolution than once a month.

Moreover, river temperature and salinity used at discharges into the model where measured at Alelyckan treatment plant water intake. Sudden drops in the river temperature are discernible and come from occasional turns to use the reserve water source from Delsjön due to closure of the river water intake. The water in Delsjön is generally a few degrees lower than the river water. Salinity measurements were uniformly within a few hundred decimals around 0.6 ‰, which were used in the model as background salinity.

The situation of modelled discharges from tributaries acquired from SMHI is not ideal either. The acquired daily modelled data ended on August 31st and mean values for discharge from the years 1990-2010 were used. The flows in the tributaries differ greatly between years and in 2011 the tributaries catchment areas seem to have been subjected to less precipitation than normal. One good aspect with daily data is that the flush from precipitation is distinguishable, yielding a more realistic model than monthly mean data. For this reason the modelled results of microbial levels from Grönån and Gårdaån within the last 17 days are questionable.

Furthermore, a mesh generated in a previous study of Göta Älv was used. Though, due to some conditions of low water levels numerical stability problems occurred not encountered in the previous study. Some of the mesh angles became too small during very low water levels. This was solved by removing some of the mesh area over Göta Älv northern part and refining mesh elsewhere. This led to decrease mesh elements which could affect the accuracy of the model. However, the changes were made at locations that deemed to be of little importance for our results. In general, a finer mesh at locations of interest is desired.

The result of the hydrodynamic simulation is compared with measurements at Lilla Edet and Lärjeholm for water level and Götaälvbron for flow and temperature. More locations along the river and more measured parameters would be desired for improved comparison.

The inactivation of indicators in the microbiological model only considers temperature and light intensity although other parameters are known to affect the inactivation. An expansion of the inactivation parameters could be executed, but then further sampling would be required. Moreover, microcosm experiment with actual river water is expected to yield better results when using more parameters. Although, changes in total organic carbon, total suspended solids, biological oxygen demand and other parameters could be expected in the future as a result of increased surface run-off. Perhaps a large scale microcosm investigation at one time is more cost efficient than several updated microcosm experiments throughout the years.

Future scenario

The complexity in the water systems, due to climate change effects means that predictions and models of future scenarios are very uncertain. In our study we assumed close to worst case scenarios for the year 2100. This assumption may not be the most realistic for a long model time frame. Though, for extreme summer water flows the scenario could yield good indication of what is to be expected in the future.

The future scenario is not intended to describe future behaviour of the hydrodynamics of the river, but merely investigate changes in microbial levels reaching the raw water intake with respect to changes in the temperature, flow and water level. Increased flows are expected to result in shorter travel times and higher sea water level could press up sea water further upstream contaminating the water intake with high salinity levels. The result of other hydrodynamic and microbial inactivation aspects due to climate change like more frequent extreme weather events, the melting of polar ice caps, solar radiation intensity, etc. is difficult to model due to lack of data.

Recommendations for further investigation

For further investigation of microbial inactivation and transportation, more frequent and longer time frame for sampling and measurements would yield more valid result. To investigate only summer conditions is not representative for the whole year. The hydrodynamic model needs calibration and validation of slope. Also a refinement of the mesh in order to better represent the river at some locations would be desired.

For the microbiological model, addition of CSOs and SSOs to fill the gaps of information of impact sources at Lärjeholm would be recommended.

Furthermore, a microcosm experiment for Göta Älv is considered to be important for inactivation data accuracy.

7 Conclusions

In performing this study of Göta Älv the following aspects can be concluded:

- The resulting impacts from the two tributaries Grönån and Gårdaån at the drinking water intake at Lärjeholm are less than 0.5% of the total levels of *E. coli*, and similar results for *Norovirus* and somatic coliphages.
- Addition of CSOs and SSOs would reduce the amount of unknown sources in the study, now representing close to 60% of the measured amounts at Lärjeholm. With the point sources included, a refined proportion of diffusive sources at the Göta Älv brink could be determined at different spatial intervals.
- Validation and calibration of the hydrodynamics in respects to bathymetry, mesh, hydrodynamic and water quality model are desired. Preferably with older data than used in this study. This would increase the accuracy of model, which was found to be inexact at regarding some parameters at some occasions.
- Microcosm experiment in Göta Älv would increase accuracy of microbial decay model and more frequent measurements of faecal indicators, or at least measurements at the same time steps at all locations would improve the accuracy of modelled outcomes.
- The water quality model in this study that was developed based on the results of hydrodynamic model can be used in environmental risk management.

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