Hydrodynamic Modelling of Microbial Water Quality in a Drinking Water Source

Ekaterina Sokolova, Thomas J.R. Pettersson, Olof Bergstedt and Malte Hermansson

Abstract The presence of faecal contamination in drinking water sources can cause waterborne disease outbreaks. The aim of this article was to study the influence of wastewater discharges from a wastewater treatment plant on microbial water quality in a drinking water source—the river Göta älv in Sweden. To fulfil this aim, the fate and transport of the faecal indicators E. coli and somatic coliphages in the river Göta älv were simulated using a three-dimensional hydrodynamic model. The validation of the hydrodynamic model confirmed a good model performance: the correlation coefficient was 0.99; the absolute mean difference between the simulated and measured water surface elevation was 0.03 m, which is 11.1 % of the standard deviation of the measured data. The modelling results revealed that during overflow events at the wastewater treatment plant, discharges of untreated wastewater contributed more to the concentrations of faecal indicators at the water intake than discharges of treated wastewater. The hydrodynamic modelling of microbial water quality proved to be a useful tool to estimate the contribution of different sources to the total contamination of raw water used for drinking water supply and, therefore, to provide decision-support information for preventive and mitigative risk-reduction measures.

Introduction

The faecal contamination of drinking water sources is a common cause of waterborne disease outbreaks [4, 7]. Faecal contamination often enters a drinking water source from a variety of contamination sources, such as wastewater treatment plants

E. Sokolova (✉) · T. J. Pettersson · O. Bergstedt
Water Environment Technology, Chalmers University of Technology, 412 96,
Gothenburg, Sweden
e-mail: ekaterina.sokolova@chalmers.se

O. Bergstedt
Göteborg Vatten, Göteborgs Stad, Box 123, 424 23, Angered, Sweden

M. Hermansson
Department of Cell and Molecular Biology, Microbiology, University of Gothenburg,
405 30, Gothenburg, Sweden

(WWTPs), on-site sewers, sewer overflows, as well as surface runoff from urban and agricultural areas. To prevent and mitigate the faecal contamination of drinking water sources, estimation of the contribution of different sources to the total contamination is required.

To estimate the contribution of different sources to the total contamination of a water source at a certain location, hydrodynamic modelling of the microbial water quality can be used. Hydrodynamic modelling proved to be useful to simulate the fate and transport of faecal contamination within the water source, e.g. [5, 6, 9, 10, 12, 14, 16].

The aim of this article was to study the influence of wastewater discharges from a wastewater treatment plant on the water quality in the river Göta älv at the water intake of a drinking water treatment plant in Gothenburg, Sweden. For this purpose, a three-dimensional hydrodynamic model was set up and validated in order to simulate the fate and transport of faecal indicators (*E. coli* and somatic coliphages) within the river.

Materials and Methods

Study Area

Göta älv is a river that drains Lake Vänern into the strait Kattegat at the city of Gothenburg on the west coast of Sweden. The total catchment area of the river Göta älv is 50,233 km^2, which constitutes approximately 10 % of the area of Sweden. The part of the catchment area that is located downstream of Lake Vänern is approximately 3500 km^2. The length of the river between the outflow from Lake Vänern and the mouth of the river is 93 km. The vertical drop of the river is approximately 44 m. The water flow in the river Göta älv is regulated by several hydropower stations and varies strongly; the average and the maximum water flows are approximately 550 and 1000 m^3/s, respectively. Upstream of the island Hisingen, the river splits into two branches; the northern branch—Nordre älv—transports from 2/3 to 3/4 of the total water flow, the southern branch keeps the name Göta älv and runs towards the city of Gothenburg [3].

The river Göta älv is used for many various purposes, among which are drinking water production, transportation, hydropower, fish farming and sport fishing. The river is used as a water source for the drinking water supply of approximately 700,000 consumers in several municipalities, among which Gothenburg with approximately 500,000 consumers. Along the river there are five raw water intakes; the water intake for the drinking water treatment plants in Gothenburg (Lackarebäck and Alelyckan) is called Lärjeholm.

Between Lake Vänern and the Lärjeholm water intake the river Göta älv receives wastewater from approximately 100,000 persons. Approximately 95 % of this wastewater is treated at municipal wastewater treatment plants, while 5 % is

treated by on-site sewer systems [3]. On the stretch between Lake Vänern and the Lärjeholm water intake, there are eight wastewater treatment plants that use the river Göta älv as a recipient of wastewater. The wastewater treatment plant Älvängen in the municipality of Ale treats wastewater from approximately 6200 people and is located approximately 24 km upstream of the Lärjeholm water intake.

The wastewater treatment at the Älvängen WWTP consists of mechanical, biological and chemical treatment steps [17]. The mechanical treatment includes a bar screen, grit chamber and primary sedimentation. The biological treatment includes an aeration tank and two sedimentation tanks. The chemical treatment involves chemical dosage, flocculation tanks and sedimentation tanks [17]. During heavy rainfalls, the overflows from this wastewater treatment plant can occur due to stormwater intrusion into sewer networks, i.e. the incoming wastewater can be discharged to the river Göta älv after only passing the primary sedimentation treatment step (partly treated wastewater) or occasionally even without any treatment (untreated wastewater).

In order to study the influence of wastewater discharges from the Älvängen WWTP on the raw water quality at the Lärjeholm water intake, the model was set up to cover the approximately 60 km long river stretch located between Lilla Edet (downstream of the hydropower station) and the Gothenburg harbour in the Kattegat. The length of the river stretch between Lilla Edet and the Älvängen WWTP is approximately 20 km and between Lilla Edet and the Lärjeholm water intake—approximately 44 km.

Model Implementation

To simulate the hydrodynamic conditions in the river Göta älv, the three-dimensional time-dependent hydrodynamic model MIKE 3 FM [2] was used. This hydrodynamic model is based on the numerical solution of three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure [2]. The model consists of continuity and momentum equations and is closed by a turbulent closure scheme [2]. The water density was assumed to be homogenous (barotropic formulation).

The modelling domain was approximated with prisms (triangles in horizontal plane) using a flexible mesh approach. The length of the triangles' sides varied from approximately 50 to 90 m. In vertical direction, the river was divided into 10 layers with a thickness that could vary depending on the depth and water surface elevation in the river (sigma-layers).

The initial conditions in the river were defined by the observed water surface elevation (Table 1). The upstream and downstream boundary conditions were defined by time-series of data regarding the water flow through the hydropower station in Lilla Edet, the water flow in the northern branch of the river—the river Nordre älv and the water surface elevation at the Gothenburg harbour (Table 1). On the land boundary the normal component of velocity was set to zero.

Table 1 Input data used for setup and validation of the hydrodynamic model of the river Göta älv

Type of data	Resolution	Source
Bathymetry	10 m	SGI[a]
Bathymetry	20 m	Sjöfartsverket[b]
Wind speed and direction	1 h	Göteborgs Stad
Precipitation	1 day	SMHI[c]
Water flow in tributaries	1 day	SMHI[c]
Water surface elev. and flow at Lilla Edet	1 h	Vattenfall
Water surface elev. at Lärjeholm water intake	1 h	Göteborg Vatten
Water surface elev. at Gothenburg harbour	1 h	SMHI[c]

[a] Swedish Geotechnical Institute. Data covered the part of the river between Lilla Edet and the mouth of the river Säveån
[b] Swedish Maritime Administration. Data covered the part of the river between the mouth of the river Säveån and the Gothenburg harbour
[c] Swedish Meteorological and Hydrological Institute

The model was set up to account for the hydrometeorological conditions (wind and precipitation on the river surface) and the inflow to the river from the tributaries with catchment areas greater than 50 km^2 (tributaries Gårdaån, Lärjeån, Grönån, Säveån, Hältorpsån and Mölndalsån; Table 1). The horizontal and vertical eddy viscosities were simulated using Smagorinsky and Log law formulations, respectively [2]. The bed resistance was described by a constant roughness height of 0.05 m. The model was run with default parameterisation [2].

The fate and transport of faecal indicators in the river Göta älv were simulated using the microbial water quality model ECO Lab [1], which was coupled with the hydrodynamic model of the river. The microbial water quality model used flow fields from the hydrodynamic model to calculate the faecal indicator concentrations in the river.

In the microbial water quality model, the decay of faecal indicators was described according to Eq. 1:

$$\frac{dC}{dt} = -k \cdot C$$

(1)

where k is the decay rate of faecal indicators in the water, t is the time and C is the faecal indicator concentration.

The decay coefficient for *E. coli* and somatic coliphages in the river was described by Eq. 2 [8, 13]:

$$k = k_0 \cdot \theta_I^{Int} \cdot \theta_T^{(Temp-20)}$$

(2)

where k_0 (1/day) is the decay rate at 20 °C for a salinity of 0 ‰ and darkness; θ_I is the light coefficient; *Int* (kW/m^2) is the light intensity integrated over depth; θ_T is the temperature coefficient; *Temp* (°C) is the water temperature.

The coefficients in Equation 2 for *E. coli* and somatic coliphages were experimentally determined in the microcosm trials performed in different seasons for the conditions of Lake Rådasjön in Sweden [13]. The coefficients k_0, θ_I and θ_T were set to 0.76, 1 and 1.04 for *E. coli* and to 0.25, 1 and 1.08 for somatic coliphages, respectively.

Validation of Hydrodynamic Model

To assess the performance of the hydrodynamic model, validation was performed by comparing the simulated and measured water surface elevation at the Lärjeholm water intake (Table 1). In order to capture different hydrodynamic conditions, validation was performed on four time periods, which were selected based on the water flow in the river during year 2011: low and stable (1–31 May), low and varying (15 June–16 July), high and stable (25 August–25 September), as well as high and varying (10 November–11 December). The validation showed that the model described the measured data very well—the Pearson correlation coefficient was 0.99 ($p<0.001$). The absolute mean difference between the simulated and measured water surface elevation was 0.03 m. This absolute mean difference and its standard deviation were 11.1% and 13.8% of the standard deviation of the measured data, respectively. An example of the congruence between the simulated and measured data during one of the selected periods is shown in Fig. 1.

Simulations

During year 2011, several overflow events from the Älvängen WWTP into the river Göta älv occurred (Fig. 2). Several of these overflow events coincided in time with peaks of measured *E. coli* concentration at the Lärjeholm water intake (Fig. 2). Based on the data on overflow events and peaks in *E. coli* concentration in raw water, two time periods were selected to be simulated to study the influence of overflow events from the Älvängen WWTP on the raw water quality at the Lärjeholm water intake: 7–21 January (event I) and 4–24 September (event II). In the simulations of these two periods, the discharges of different types of wastewater were assigned constant concentrations of faecal indicators (Table 2) and the water temperature for event I and event II was specified as 4 °C and 18 °C, respectively.

The simulation of event I was also performed with the assumption that there was no decay of faecal indicators.

Fig. 1 Measured (*red dotted line*) and simulated (*black line*) water surface elevation at the Lärjeholm water intake
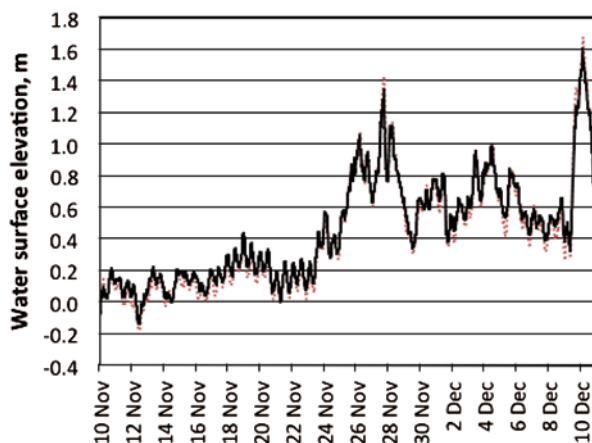
Results

The simulation of event I with no decay of *E. coli* and somatic coliphages resulted in up to 68 % and 9 %, respectively, higher values than the simulation with decay described based on the experimental measurements (Fig. 3).

The modelling results showed that, in case of both event I and event II, discharges of untreated wastewater from the Älvängen WWTP contributed the most to the concentrations of faecal indicators at the water intake in comparison to partly treated and treated wastewater (Figs. 4 and 5). The contribution of discharges of partly treated and treated wastewater to faecal indicator concentrations at the water intake was relatively small (Figs. 4 and 5).

According to the modelling results, it took between 26 and 31 hours in case of event I (Fig. 4) and 13 and 25 hours in case of event II (Fig. 5) before the discharges of untreated wastewater from the Älvängen WWTP caused peaks of faecal indicator concentrations at the Lärjeholm water intake.

Discussion and Conclusions

In this study a hydrodynamic model of the river Göta älv was set up and successfully validated (Fig. 1; cf. [16]). This hydrodynamic model was then used to simulate the fate and transport of the faecal indicators *E. coli* and somatic coliphages in the river, in order to evaluate the influence of wastewater discharges from the Älvängen WWTP during two overflow events on the microbial water quality at the Lärjeholm water intake. The model illustrated that during two studied events the discharges of untreated wastewater accounted for most of the Älvängen WWTP's contribution to the contamination at the Lärjeholm water intake (Figs. 4 and 5).

Table 2 Concentrations of faecal indicators E. coli and somatic coliphages in wastewater discharges from wastewater treatment plant. a Concentrations used in the model were calculated as median values of the concentrations measured at the Arvidstorp WWTP (municipality of Trollhättan, Sweden).

Wastewater	E. coli, CFU/100 mL (No of measurements)	Somatic coliphages, PFU/100 mL (No of measurements)
Treated	34,000 (17)	11,000 (14)
Partly treated	120,000 (13)	32,000 (12)
Untreated	450,000 (16)	100,000 (13)

Fig. 2 a Discharges of untreated (*red line*), partly treated (*blue line*) and treated (*green line*) wastewater from the Älvängen WWTP (data provided by the municipality of Ale, Sweden) and **b** *E. coli* concentrations in raw water at the Lärjeholm water intake (data provided by Göteborg Vatten)
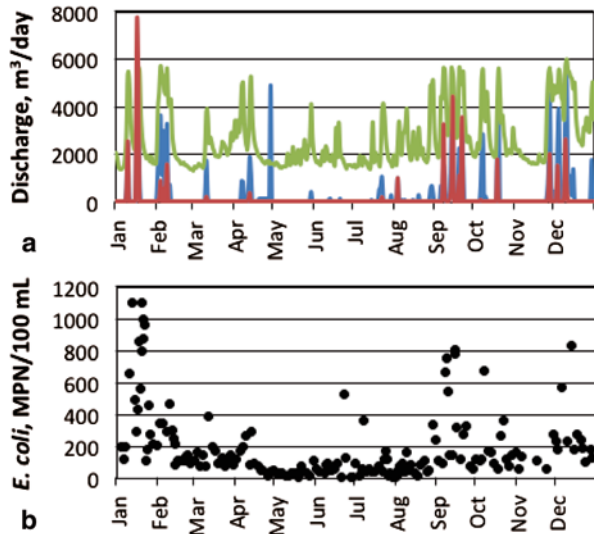
Although the discharges of untreated wastewater from the Älvängen WWTP coincided in time with high measured concentrations of *E. coli* at the Lärjeholm water intake (Fig. 2), the modelling results showed that only a small part of this faecal contamination at the water intake can be attributed to the influence of discharges from the Älvängen WWTP (Figs. 4 and 5). Along the river Göta älv there is a number of other faecal contamination sources, which, most likely, release faecal contamination during the same time periods as the Älvängen WWTP and contribute to the faecal contamination at the Lärjeholm water intake.

Pathogens are often very persistent in water sources [11, 15]. To estimate the infection risks related to the presence of pathogens in raw water, somatic coliphages, due to their slower decay, constitute a more suitable indicator than *E. coli*. This was shown by the simulations with the assumption that there was no decay of faecal indicators (Fig. 3). Detection of low *E. coli* concentrations may lead to underestimation of infection risks, as high levels of pathogens may still be present in the absence of *E. coli*.
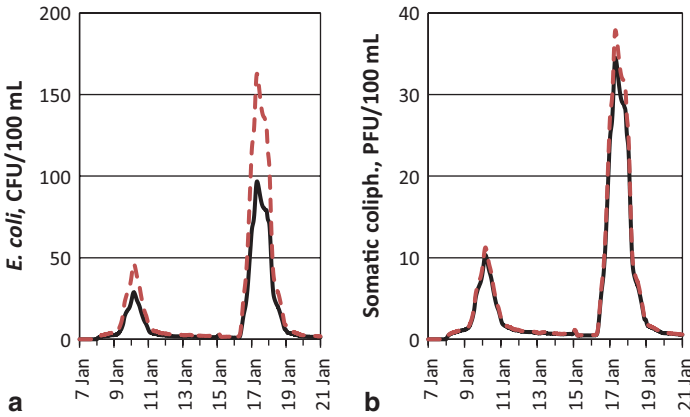
Fig. 3 Simulated *E. coli* (**a**) and somatic coliphages (**b**) concentrations in raw water at the Lärje-holm water intake during event I, assuming decay (*black line*) and assuming no decay (*red dotted line*)

Fig. 4 Graph (**a**) shows discharges of untreated (*red line*), partly treated (*blue line*) and treated (*green line*) waste water from the Älvän-gen WWTP into the river Göta älv. Graphs (**b**) and (**c**) represent the simulated contribution of untreated (*red line*), partly treated (*blue line*) and treated (*green line*) waste water discharges to the *E. coli* (**b**) and somatic coliphages (**c**) concentrations in raw water at the Lärjeholm water intake during event I. The total contribution from the Älvängen WWTP is represented by the *black line* in graphs (**b**) and (**c**)
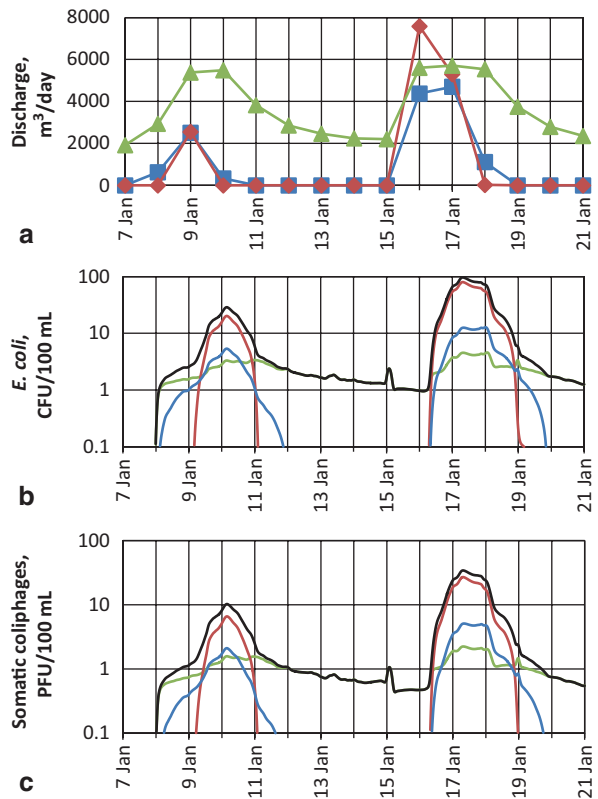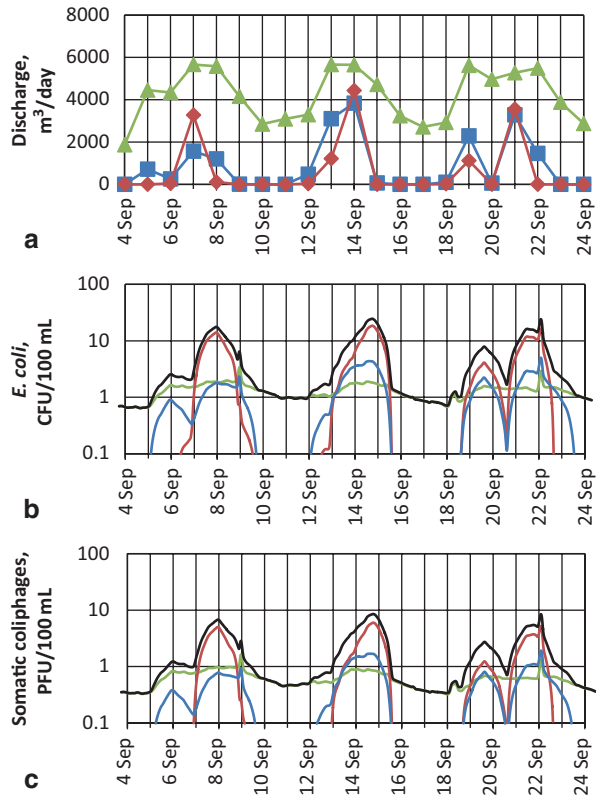
Fig. 5 Graph (**a**) shows discharges of untreated (*red line*), partly treated (*blue line*) and treated (*green line*) waste water from the Älvängen WWTP into the river Göta älv. Graphs (**b**) and (**c**) represent the simulated contribution of untreated (*red line*), partly treated (*blue line*) and treated (*green line*) waste water discharges to the *E. coli* (**b**) and somatic coliphages (**c**)

The hydrodynamic modelling of the microbial water quality proved to be a powerful tool to determine the contribution of different sources to the total contamination at the water intake. It can also provide information about the time that it takes for the peak of concentration to reach the water intake (Figs. 4 and 5). This type of modelling can be used to simulate various scenarios and situations, in order to estimate and predict the influence of different contamination events on the microbial water quality under various conditions. Therefore, hydrodynamic modelling can facilitate decision-making regarding risk-reduction measurements in the context of the faecal contamination of drinking water sources.

References

 1. DHI (2004) MIKE 21/3 Ecological modelling: MIKE21/3 ECO Lab FM short description. DHI Water & Environment, Horsholm
 2. DHI (2011) MIKE 21 & MIKE 3 Flow model FM hydrodynamic and transport module—scientific documentation. DHI Water & Environment, Horsholm
 3. GÄVVF (2006) Facts about the river Göta älv: a description of the river Göta älv and its surroundings 2005. (In Swedish: "Fakta om Göta älv: en beskrivning av Göta älv och dess omgivning 2005"). Göta älvs Vattenvårdsförbund (GÄVVF)—water management association of the river Göta älv, Gothenburg
 4. Hrudey SE, Hrudey EJ (2004) Safe drinking water: lessons from recent outbreaks in affluent nations. vol 3. IWA Publishing, London
 5. Kashefipour SM, Lin B, Falconer RA (2006) Modelling the fate of faecal indicators in a coastal basin. Water Res 40(7):1413–1425
 6. Liu L, Phanikumar MS, Molloy SL, Whitman RL, Shively DA, Nevers MB, Schwab DJ, Rose JB (2006) Modeling the transport and inactivation of E. coli and enterococci in the near-shore region of Lake Michigan. Environ Sci Technol 40(16):5022–5028
 7. Mac Kenzie WR, Hoxie NJ, Proctor ME, Gradus MS, Blair KA, Peterson DE, Kazmierczak JJ, Addiss DG, Fox KR, Rose JB, Davis JP (1994) A massive outbreak in Milwaukee of Cryptosporidium infection transmitted through the public water supply. New Engl J Med 331(3):161–167
 8. Mancini JL (1978) Numerical estimates of coliform mortality rates under various conditions. J Water Pollut Control Federation 50(11):2477–2484
 9. Riou P, Le Saux JC, Dumas F, Caprais MP, Le Guyader SF, Pommepuy M (2007) Microbial impact of small tributaries on water and shellfish quality in shallow coastal areas. Water Res 41(12):2774–2786
10. Sanders BF, Arega F, Sutula M (2005) Modeling the dry-weather tidal cycling of fecal indicator bacteria in surface waters of an intertidal wetland. Water Res 39(14):3394–3408
11. Seitz SR, Leon JS, Schwab KJ, Lyon GM, Dowd M, McDaniels M, Abdulhafid G, Fernandez ML, Lindesmith LC, Baric RS, Moe CL (2011) Norovirus infectivity in humans and persistence in water. Appl Environ Microbiol 77(19):6884–6888
12. Sokolova E, As Ìtröm J, Pettersson TJR, Bergstedt O, Hermansson M (2012) Estimation of pathogen concentrations in a drinking water source using hydrodynamic modelling and microbial source tracking. J Water Health 10(3):358–370
13. Sokolova E, Åström J, Pettersson TJR, Bergstedt O, Hermansson M (2012) Decay of Bacteroidales genetic markers in relation to traditional fecal indicators for water quality modeling of drinking water sources. Environ Sci Technol 46(2):892–900
14. Thupaki P, Phanikumar MS, Beletsky D, Schwab DJ, Nevers MB, Whitman RL (2010) Budget analysis of Escherichia coli at a southern Lake Michigan Beach. Environ Sci Technology 44(3):1010–1016
15. Walker Jr FR, Stedinger JR (1999) Fate and transport model of Cryptosporidium. J Environ Eng 125(4):325–333
16. Zhu X, Wang JD, Solo-Gabriele HM, Fleming LE (2011) A water quality modeling study of non-point sources at recreational marine beaches. Water Res 45(9):2985–2995
17. Åström J, Pettersson TJR (2007) Wastewater discharges and microbial contamination in a drinking water source the river Göta älv (In Swedish: "Avloppsutsläpp och mikrobiologisk påverkan i råvattentäkten Göta älv"). Svenskt Vatten Utveckling, Stockholm