Identification and management of microbial contaminations in a surface drinking water source

J. Åström, T. J. R. Pettersson and T. A. Stenström

ABSTRACT

Microbial contamination of surface waters constitutes a health risk for drinking water consumers which may be lowered by closing the raw water intake. We have evaluated microbial discharge events reported in the river Göta älv, which is used for raw water supply to the city of Göteborg. Elevated levels of faecal indicator bacteria were observed during periods of closed raw water intake. High bacteria levels were, however, also occasionally detected during periods of open intake, probably as a result of microbial discharge far upstream in the river which may be difficult to predict and manage by closing the intake. Accumulated upstream precipitations, resulting in surface runoff and wastewater contaminations in the catchment, correlated positively with the levels of total coliforms, *E. coli*, intestinal enterococci and sulfite-reducing clostridia. Levels of faecal indicator organisms were negatively correlated to the water temperature due to enhanced survival at lower temperatures. Wastewater discharges from a municipality located just upstream of the water intake resulted in elevated *E. coli* concentrations downstream at the raw water intake for Göteborg. To improve the prediction of microbial contaminations within the river Göta älv, monitoring data on turbidity and upstream precipitation are of particular importance.

Key words | combined sewer overflows, indicator organisms, microbial events, precipitation, raw water, water management

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INTRODUCTION

Drinking water safety depends on the raw water quality, well functioning treatment processes and properly maintained distribution and plumbing systems. The identification and management of quality variations and hazardous events in the raw water are important when assessing the level of risks related to drinking water production and govern the potential risk for diseases associated with consumption of insufficiently treated surface water. Waterborne diseases related to poor surface water quality, in combination with insufficient treatment, still occur. In the period 1980–2004, 142 waterborne outbreaks were reported in Sweden with a total of 63,000 cases of reported illness (SMI 2006). In order to prevent microbial hazards in the surface water to present a health risk through drinking water, an understanding of the catchment and its inherent activities is needed.

Pathogens present in surface waters originate from both point- and diffuse sources and concentrations may vary considerably over time (Ferguson *et al.* 2003). Increased microbial impact have been observed during rain periods with substantial runoff, typically resulting in elevated microbial concentrations in surface waters (Tyrrel & Quinton 2003; Signor *et al.* 2005). Point sources for pathogens may include municipal wastewater discharges and heavily polluted tributaries within a river system. Diffuse sources, on the other hand, include urban, agricultural and forestry runoffs with microbial impact from livestock and wild animals in the catchment area. Furthermore, the microbial load to the raw water within the catchments is influenced by natural factors, such as climatological parameters (rain, sunlight and temperature), hydrology and topography (Taylor 2003; Kay *et al.* 2005).

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An assessment of the microbial risk associated with raw water contamination has traditionally been based on monitoring for microbial indicator bacteria and not on the actual levels of pathogens (Taylor 2003). Monitoring of raw water quality for drinking water production, as well as recreational water quality, is based on indicator bacteria like total coliforms, *E. coli* and intestinal enterococci. Bacteriophages and sulfite-reducing clostridia have sometimes been used as supplementary indicators (EC 1998). The indicator organisms may not reflect the actual risk, since a direct correlation between pathogens and traditional indicator organisms often is lacking. In a recent EU project on drinking water risks (MicroRisk) twelve European catchments, of which eight included river surface water, were evaluated and the interrelation between microbial parameters appeared to be site-specific (Dechesue & Soyeux 2007). The traditional organisms *E. coli* and faecal enterococci are, however, considered predictive in the identification of hazardous events (Prüss 1998; Kay *et al.* 2004).

In addition to traditional microbial sampling, other parameters to identify microbial hazardous events may be used. It has been observed that the levels of indicator bacteria and parasites increase considerably in the surface water as a result of extreme runoff events (Atherholt *et al.* 1998; Crowther *et al.* 2002) why rainfall monitoring may be considered as an important early warning method to forecast microbial contaminations. One of the consequences of heavy rainfalls is increased discharge from urban wastewater systems including combined sewer overflows. The discharged volumes of wastewater (Payment *et al.* 2000, 2001) as well as stormwater (Marsalek & Rochfort 2004; Selvakumar & Borst 2004) may carry substantial amounts of pathogenic bacteria, viruses and parasites and their subsequent fate in the receiving waters will reflect the risk of infections after exposure.

The aim of this paper is to assess potential hazardous events that have been monitored and reported for several years in the raw water source river Göta älv, Sweden. Closure of the raw water intake due to online and upstream reports were evaluated in relation to the microbial indicator variability. The microbial impact at the intake was correlated to external factors in the upstream catchment area, including rain, temperature, flow, turbidity and microbial effects from local precipitations and sewage discharges were further assessed.

MATERIALS AND METHODS

Study area

The city of Göteborg is located in the southwest part of Sweden and has its raw water intake from the river Göta älv. The entire catchment area, including the areas of the upstream lake Vänern and the further upstream rivers, is the largest in Sweden ($50{,}200\,\mathrm{km}^2$) and bridges the border with Norway in the north-west. The lower part of the catchment, stretching from Lake Vänern to the sea (Figure 1), comprises an area of $13{,}300\,\mathrm{km}^2$ and has an annual mean water flow of about $550\,\mathrm{m}^3\,\mathrm{s}^{-1}$. Point source pollution upstream of the raw water intake for Göteborg includes human pollution from urban wastewater systems, with about 87,500 persons connected, and 13 larger industries including paper mills discharging along the river

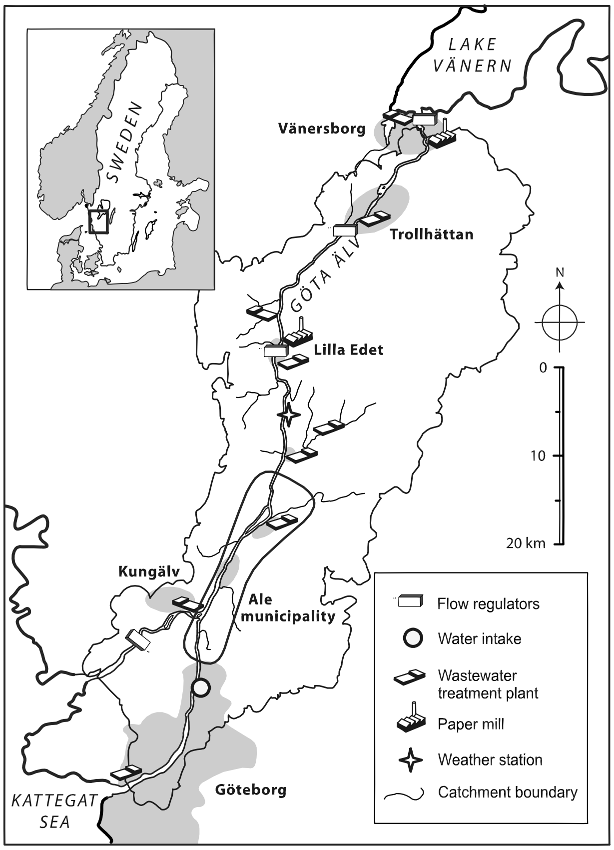

Figure 1 | The river Göta älv and its lower catchment area with the location of wastewater treatment plants, paper mills, weather station and the drinking water intake for Göteborg. The administrative border of the municipality of Ale is marked by a bold line.

(GÄWF 2006). The microbial impact from diffuse sources mainly includes surface runoffs from urban (stormwater) and livestock areas but also from birds and wild animals. The Göta älv is used as a raw water source for six drinking water treatment plants, where two are located in Göteborg. These two plants are serving in total about 700,000 people of which about 500,000 people are supplied in the city of Göteborg. At the Göteborg raw water intake, water is pumped into a storage reservoir and further pumped to the water treatment plants.

River flow

The highest flows in Göta älv are normally registered in the period from December to June, while flows below 500 $m^3 s^{-1}$ mainly occur between July to November. The seasonal flow variations registered in Lilla Edet (Figure 1) are in the range of 200–1,200 $m^3 s^{-1}$. Along the river, the flow is regulated at hydropower stations in Vänersborg, Trollhättan and Lilla Edet. These hydropower stations mainly determine the flow variations in Göta älv. In the downstream part at Kungälv, the river branches around an island. The northern branch has the largest water flow of about 75% and the southern branch (still referred to as the Göta älv) the remaining 25%. A flow shield in the northern branch, constructed to protect the surface water from salt intrusions from the sea, further regulates the flow in the southern branch of the Göta älv, with a flow in the range of 150–250 $m^3 s^{-1}$ over the year. The flow time from Lake Vänern to the sea through Göta älv varies between 1.5 and 5 d, with a mean of about 3 d (GÄWF 2006).

Wastewater and paper mill discharges

In the urban areas of the catchment south from Vänern untreated wastewater is frequently discharged to the Göta älv from the wastewater systems. These discharges originate from combined sewer overflows during heavy rainfalls or from hydraulic failures in the separate sewage systems, e.g. power failures in pumping stations and stormwater intrusions. Along the river nine municipal wastewater treatment plants are situated (Figure 1), where the largest is located in Trollhättan (47,000 persons connected). For wastewater treatment plants with more than 200 persons connected and for combined sewer overflows with more than 2000 persons connected, monitoring and sampling requirements are issued by the Swedish EPA. These are based on chemical parameters (COD_{Cr}, BOD_7, total phosphorus and total nitrogen). No requirements for monitoring of microbial discharge loads are enforced in Sweden at present for wastewater treatment plants or for sewage network discharges.

Water sampling and microbial analyses

Seven monitoring stations aimed at an early warning system for water treatment plants are located along the Göta älv between Vänern and the raw water intake for Göteborg. Parameters continuously monitored on-line are water temperature, turbidity, conductivity, redox potential and pH. Microbial sampling of indicator organisms are carried out at three stations upstream of the raw water intake: Garn, Södra Nol and Surte. At flows in the interval from 150 to 900 $m^3 h^{-1}$ the transport time from the station in Garn (next to the weather station; Figure 1) 35 km upstream of the intake, is in the range 16–66 h. From the station Södra Nol, situated in Ale municipality 18 km upstream, the transport time to the intake is in the range 9.5–39 h.

Values from analyses of samples taken in Garn (three times per week) and in Södra Nol (monthly) are accounted for by the water treatment plants in Göteborg in their decision procedure of closing the raw water intake. At the very intake point microbial samples are taken three times a week using an automated sampler. Microbial samples from these three stations are analysed for total coliforms, *E. coli*, sulfite-reducing clostridia and less frequently for intestinal enterococci. Before 2004 analyses of *E. coli* were carried out by the membrane filtration method (ISO 2000*b*) and thereafter a Colilert™ tray method has been used. Local sampling data for *E. coli* at the intake have resulted in similar concentrations from the membrane filtration and the Colilert methods, respectively, and analytical results from these two methods are therefore comparable (Braathen *et al.* 2005). Samples from the raw water intake were analysed monthly by standard membrane filtration methods for intestinal enterococci (ISO 2000*a*). From 2004 samples taken three times a week are also analysed for sulfite-reducing clostridia according to the standard (ISO 1986) except for the preheating to exclude vegetative cells.

Raw water intake management

The raw water intake for Göteborg from the river Göta älv is designed to close if the raw water quality is considered unacceptable for drinking water production. In order to prevent a variety of contaminations within the catchment, closures of the intake are decided from water quality monitoring and upstream reports. These closures of the intake (closure events) may relate to microbial and non-microbial contaminations (Table 1) and are here consecutively numbered for analyses.

Microbial contaminations are identified from microbial quality (MQ) analyses at the raw water intake (category no. 1, Table 1) and at the upstream sampling stations (no. 2); predominantly high concentrations of *E. coli* and total coliforms. In agreement with the former Swedish national standard for raw water quality (SLV 1989), withdrawn in 2003, *E. coli* levels above 500 CFU, 100 mL^{-1} and total coliforms above 5,000 CFU 100 mL^{-1} are used as decision levels for closing the raw water intake. After the coliform method changes, from membrane filtration to Colilert analysis in 2004, the threshold level for *E. coli* was in the management set to 400 MPN 100 mL^{-1} in order to stay below the level at 500 CFU 100 mL^{-1}. Microbial contaminations are also identified in reports from the upstream catchment but also from high precipitation records (no. 3). Reports on microbial contaminations during recent years have included discharges from untreated urban wastewater such as combined sewer overflows (no. 4), paper mill industries (no. 5) and manure contaminations from livestock. An accident with manure spread (no. 6) occurred in May 2001 when a tank containing about 1,000 m^3 of manure burst in the Göta älv catchment 35 km upstream of the Göteborg raw water intake.

Closure events due to non-microbial contaminations (no. 8) are related to elevated salt levels (chlorine concentrations) from backflow of sea water, fluctuations of online measurements of pH or redox potential, high turbidity (at low bacteria counts) or oil spills in the river. Other hazardous non-microbial events in the river catchment area, such as building activities in the river, also resulted in closure of the intake (included in category no. 8).

Table 1 | Closures of the intake 2001–2004 due to microbial and non-microbial events, and corresponding number of samples taken for total coliforms (TC), *E. coli* (EC), intestinal enterococci (IE) and sulfite-reducing clostridia (SRC). MQ = Microbial Quality

			Duration (h)		Number of samples (*N*)			
Closure event	**Category**	**Events (*N*)**	**Sum**	**Max.**	**TC**	**EC**	**IE**[1]	**SRC**[2]
Microbial	1. Intake MQ alarms	10	547	141	12	12	1	10
	2. Upstream MQ alarms	12	783	145	33	33	5	12
	3. Heavy rainfalls	5	395	128	13	13	0	2
	4. Wastewater discharges	28	1,803	227	57	57	5	5
	5. Papermill discharges	14	800	147	28	28	2	7
	6. Manure accident	1	110	110	4	4	0	0
	7. Unspecified reports	21	1,170	143	47	46	5	6
Non-microbial	8. Salt, Oil, Turbidity or Others	144	2,626	233	59	59	3	5
Accepted water	9. Open intake				476	473	44	103

[1] Intestinal enterococci sampled monthly.

[2] Sulfite-reducing clostridia only sampled during 2004.

In Table 1 the frequency and total time of these closure events, as well as time periods with open intake (accepted water, no. 9), are presented for the years 2001–2004. The total numbers of microbial samples taken during the regular monitoring for the different closure event categories and for time periods with open intake are presented. As shown in the table, microbial closure events represented the longest period when the intake was closed. Among the microbial events, wastewater discharges was the most frequent and lasted for a maximum of 227 h. Closures due to unspecified reports on microbial events (no. 7) also occurred frequently and especially during the years 2001–2003. During these years the specification of microbial contaminations and reports (i.e. nos. 4, 5 and 6) were less frequently registered by the raw water intake regulators in Göteborg. Non-microbial events frequently closed the intake, though a majority of these only lasted for a few hours.

Data collection

Data from microbial analyses within the regular monitoring of faecal indicator bacteria at the water intake (Table 1) were used to evaluate the closure management by comparing the microbial load for different types of events. As shown in the table, the frequency of available microbial registrations varied between different types of events and between different indicator bacteria. Data collected at the intake also included temperature and turbidity registered for each microbial sample. Also, river flow data at the raw water intake as registered by the hydropower authorities were collected.

Discharges from wastewater systems monitored in the municipality of Ale (Figure 1) during July to December 2004 were specifically used to evaluate the relative impact of wastewater discharges in the river and relate to the variation of *E. coli* at the intake point. In Ale, all wastewater discharges at the sewer network originated from pumping stations and the total discharge volumes were calculated from pump capacity data and operation time. The total by-passed volumes in the sewage network were 17,700 m^3 in the northern part of the municipality and 79,200 m^3 in the southern part. From the north to the south border of Ale municipality the distance to the raw water intake for Göteborg is between 6 and 26 km, which give a mean water transport time of 5–45 h, depending on the flow rate. At the wastewater treatment plant in Ale, approximately 20 km upstream of the intake, the total treated volume leaving the plant in 2004 was 790,000 m^3 and the by-passed volume of untreated wastewater was about 43,300 m^3.

Data from two weather stations were collected (precipitation and air temperature). The first station is located 35 km upstream of the intake, directly downstream from Lilla Edet (Figure 1), which was used as a representative for the entire river Göta älv. Precipitation data from this station was correlated with the microbial counts at the intake (*E. coli* and sulfite-reducing clostridia) and was used to determine the time delay for a rain event to have the maximum microbial impact at the water quality at the raw water intake for Göteborg. The second station is located 15 km north of the raw water intake, in the centre of Ale municipality, and the data was used in the assessment of the relative impact of the wastewater discharges from this municipality.

Data analysis

Microbial indicator data from the years 2001–2004 for the separate closures event categories and periods with open intake (Table 1) were presented as box plots, giving the median, interquartile range (25 and 75%), percentiles (5 and 95%) and outliers within each category. Microbial parameters and turbidity were transformed into a logarithmic scale to enable further statistical correlations. Correlations were computed to assess the delayed effect of precipitation on the occurrence of indicator organisms at the intake and the relative impact of different parameters on the variation of faecal indicator levels at the raw water intake. Pearson correlations coefficients (r) were calculated between the accumulated precipitation (mm), the river flow (m^3s^{-1}), the air and water temperature (°C), the turbidity (FNU, log values) and the levels of indicator bacteria (log values), including total coliforms and *E. coli* (units 100 mL^{-1}), intestinal enterococci (CFU 100 mL^{-1}) and sulfite-reducing clostridia (CFU 100 mL^{-1}).

The microbial impact of the raw water quality at the intake from wastewater discharges in Ale municipality during the second half of the year 2004 was assessed in relation to precipitation and wastewater discharge volumes (the sum of the current and previous day) using linear regression analyses (r^2-values).

RESULTS

Closures of the raw water intake for Göteborg undertaken to counteract hazardous concentrations in the drinking water were investigated in terms of indicator counts in the river, as presented in Figures 2 and 3. The levels of total coliforms and *E. coli* at the raw water intake during periods with closed intake, subdivided into the defined closure event categories, were highly varying (Figure 2). Non-microbial closure events (no. 8; Figures 2(A) and (B)) in general included lower indicator counts than microbial closure events related to alarms or specific discharges (nos. 1–5). During periods with open intake (no. 9), the levels were as a median lower compared to the periods with closed intake resulting from microbial closure events (nos. 1–5 and 7). The closure related to the single manure accident (no. 6) included a few samples ($n = 4$) and with low levels of total coliform and *E. coli*.

During periods with closed intake due to microbial concentrations or events (nos. 1–7), elevated levels of total coliforms and *E. coli* were observed in various degrees. The highest levels of total coliforms at the intake were observed during microbial closure events related to high bacteria counts upstream (median 2200 units 100 mL^{-1}) with a maximum count of 17,000 units 100 mL^{-1}. Closure events due to microbial quality alarms at the intake corresponded to slightly lower levels during the subsequent closed period. This may be explained by the delay due to microbial analysis, as acceptably low microbial loads after closure events at the intake were not immediately registered. For *E. coli* the highest mean values were observed when closures were triggered by high precipitation events, and high counts at the intake (median 300 and 290 units 100 mL^{-1}, respectively). Closures due to (reported) wastewater discharges also included comparably high *E. coli* counts (median 280 units 100 mL^{-1}), and the reporting of these was therefore helpful to exclude raw water with high loads of *E. coli*. For periods with open intake (event no. 9), when the median levels of total coliforms (395 units 100 mL^{-1}) and *E. coli* (70 units 100 mL^{-1}) were lower, samples at high levels were occasionally observed. The maximum level of total coliforms and *E. coli* during periods with open intake was as high as 12,000 and 1,100 units 100 mL^{-1}, respectively.

The levels of intestinal enterococci and sulfite-reducing clostridia during periods of open and closed intake are

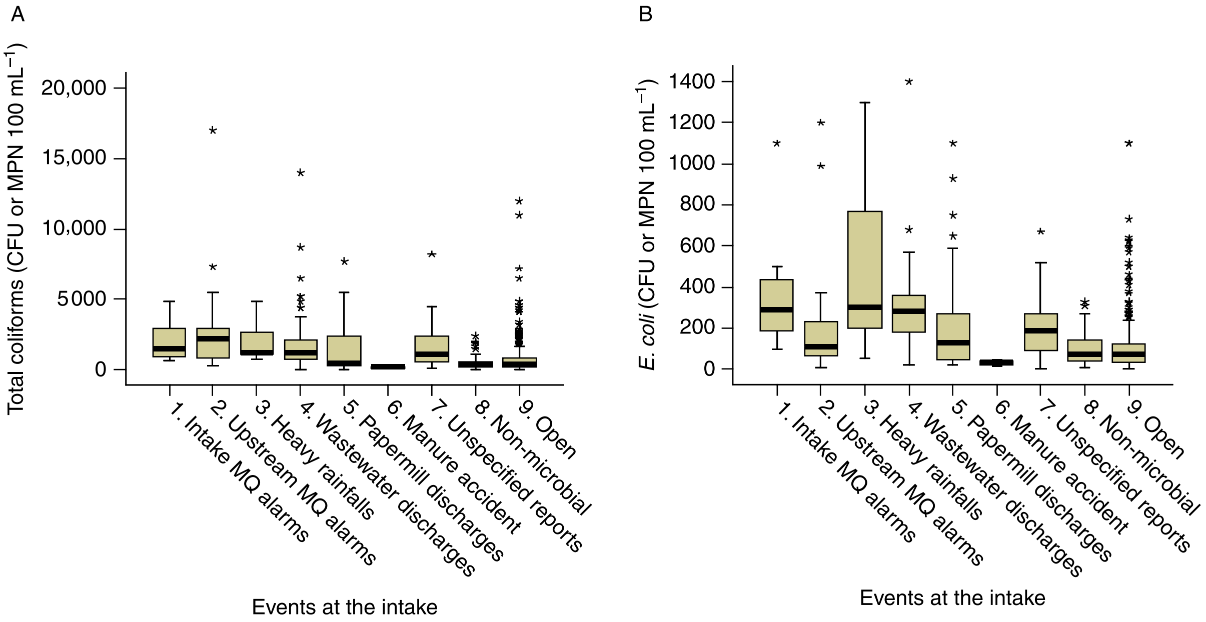

Figure 2 | Levels of (A) total coliforms and (B) *E. coli* at the water intake for different categories of microbial (nos. 1–7; MQ = Microbial Quality) and non-microbial (no. 8) closure events and for periods with open intake (no. 9) during the years 2001–2004.

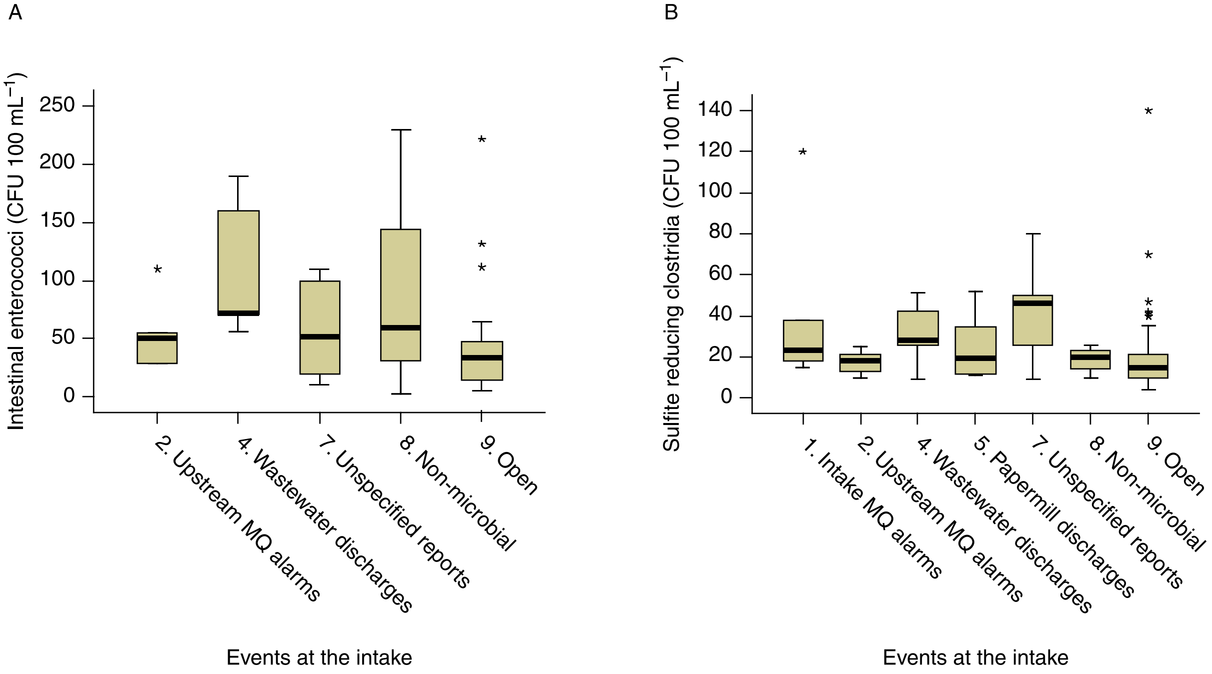

Figure 3 | Levels of (A) intestinal enterococci (measured monthly during 2001–2004) and (B) sulfite-reducing clostridia (measured three times per week in 2004) at the water intake for different categories of microbial (nos. 1–7; MQ = Microbial Quality) and non-microbial (no. 8) closure events and for periods with open intake (no. 9). Closure events including very few microbial samplings ($n = 1$ or 2) were not included in the figures.

summarised in Figure 3. Highly varying levels of intestinal enterococci, though based on relatively few data, were observed during periods of closed intake (Figure 3(A)). During periods when the intake was open (no. 9, $n = 44$), values above the 95% percentile were observed for the enterococci in three occasions. Peak values for the enterococci registered during periods with open intake, at a maximum 220 CFU 100 mL^{-1}, indicate a risk due to elevated microbial loads within the drinking water production. The relatively high counts during periods of closed intake due to wastewater discharges, based only on a few samples (no. 4, $n = 5$) however, indicate the human source as a significant source for enterococci. Non-microbial closure events (no. 8) also included high counts of enterococci in the raw water, represented by only three samples, however. For the persistent sulfite-reducing clostridia, registered only during 2004 (Figure 3(B)), the highest median concentrations (46 CFU 100 mL^{-1}) were observed during microbial closure events related to unspecified reports (no. 7, $n = 6$), thus with unknown origin. During periods with open intake (no. 9, $n = 103$) the median values were lower: however, peak concentrations were observed with a maximum at 140 CFU 100 mL^{-1}. As for the other bacteria, this indicates a substantial microbial load also during periods where the water at the intake was considered as microbially safe.

Correlating microbial data

The microbial impact in the river at the water intake was correlated to precipitation monitored at the meteorological station in Garn (35 km upstream of the intake). In Figure 4, the correlations between the concentration of total coliforms and *E. coli* and precipitation the previous day are illustrated. A positive significant correlation was observed for total coliforms and rainfall 0–5 d earlier and for *E. coli* and rainfall 1–4 d earlier (Figures 4(A) and (B), respectively). As the transport time from the meteorological station is estimated to be in the range of 16–66 h, these results indicate a delay either due to water transport or due to the dispersion and diffusion spread of bacteria in the river channel. Based on these observations, the accumulated precipitation 1–4 d prior to the microbial samplings was used in the further assessments.

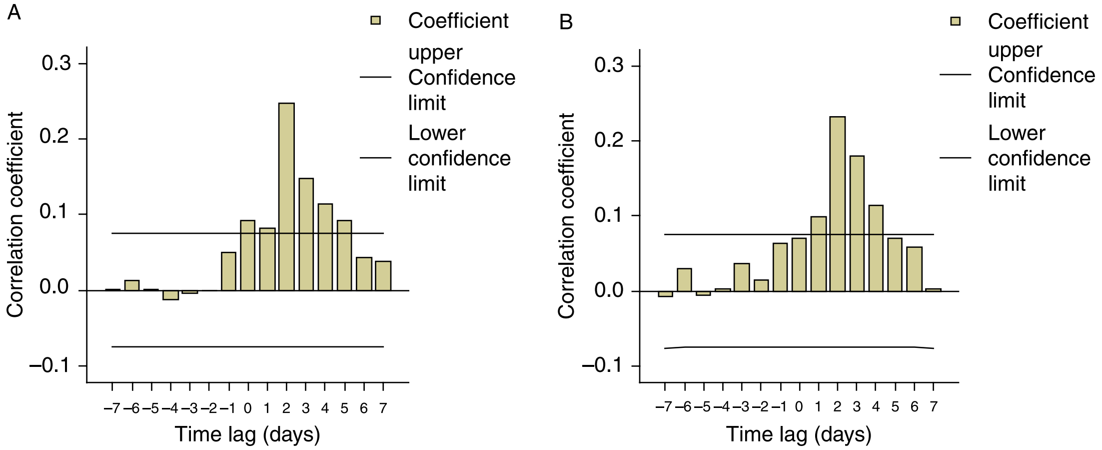

Figure 4 | Correlation coefficients (*r* values) presented as the time delay between measured rain depths, from the weather station in Garn 35 km upstream of the intake, and the logged values of total coliforms (A) and *E. coli* (B) at the raw water intake for Göteborg. The 95% confidence interval limits indicate significant correlations.

The correlation coefficients between the microbiological parameters and river flow, precipitation and temperature are summarized in Table 2. Significant correlations were found between the amount of rainfall and turbidity ($r = 0.14$) and also levels of total coliforms ($r = 0.42$), *E. coli* ($r = 0.47$), intestinal enterococci ($r = 0.56$) and sulfite-reducing clostridia ($r = 0.35$). The correlation coefficients between the river flow versus the indicator bacteria were small and negative for total coliforms ($r = -0.17$) and slightly positive for the sulfite-reducing clostridia ($r = 0.18$), indicating that the river flow as such did not influence the microbial levels in the surface water. This was explained by the flow regulations of the river and that the flow at the intake predominantly depends on the water division at the flow shield and regulations at the upstream hydroplants rather than rainfall. As presumed a clear correlation was seen

Table 2 | Pearson correlations coefficients including the precipitation (accumulated rain depths, PREC) and air temperatures (AT) 35 km upstream of the intake. Data from the intake included flow (Q), water temperatures (WT), turbidity (TURB), total coliforms (TC), *E. coli* (EC), intestinal enterococci (IE) and sulfite-reducing clostridia (SRC). Statistics represent the years 2001–2004 and significant correlations ($p < 0.05$) are marked in bold

	PREC	Q	AT	WT	TURB (log)	TC (log)	EC (log)	IE (log)	SRC (log)
PREC	1	−0.03	0.06	**0.06**	**0.41**	**0.42**	**0.47**	**0.56**	**0.35**
Q	−0.03	1	**−0.32**	**−0.28**	**0.14**	**−0.17**	**−0.14**	**−0.05**	**0.18**
AT	**0.06**	**−0.32**	1	**0.88**	**−0.19**	**−0.16**	**−0.32**	**−0.31**	**−0.38**
WT	0.06	**−0.28**	**0.88**	1	**−0.21**	**−0.22**	**−0.34**	**−0.36**	**−0.45**
TURB (log)	**0.41**	**0.14**	**−0.19**	**−0.21**	1	**0.46**	**0.40**	**0.46**	**0.65**
TC (log)	**0.42**	**−0.17**	**−0.16**	**−0.22**	**0.46**	1	**0.61**	**0.54**	**0.50**
EC (log)	**0.47**	**−0.14**	**−0.32**	**−0.34**	**0.40**	**0.61**	1	**0.71**	**0.63**
IE (log)	**0.56**	−0.05	**−0.31**	**−0.36**	**0.46**	**0.54**	**0.71**	1	**0.35**
SRC (log)	**0.35**	**0.18**	**−0.38**	**−0.45**	**0.65**	**0.50**	**0.63**	**0.35**	1

between the different microbial indicators; the highest between the *E. coli* and the intestinal enterococci ($r = 0.71$).

In the comparison between turbidity and the indicator bacteria, the highest correlation was observed with the clostridia counts ($r = 0.65$). The indicator bacteria counts were negatively correlated with the air temperature and even more negatively correlated with the water temperature. This confirms a more rapid die-off for the bacteria at higher water temperatures, and the same pattern was also found in the relation between turbidity and temperature. A positive correlation was observed between turbidity and the accumulated precipitation probably due to high surface water runoffs from both urban and rural areas (Table 2).

The relative impact from local precipitations and wastewater discharges

Local precipitations and wastewater overflow volumes registered from the Ale municipality (municipality border marked in Figure 1) were correlated to the downstream *E. coli* counts at the water intake for Göteborg. A maximum overflow volume of 31,400 m^3 was registered during two days, exceeding the highest volumes passing the WWTP (10,000 m^3 during 2 d). In Figure 5(A) the *E coli* concentration at the raw water intake is plotted as a function of the discharge volumes registered in Ale municipality the same day as the indicator analyses and the day before. A weak but positive trend was observed between *E. coli* counts at the water intake and the discharged wastewater volumes ($r^2 = 0.16$). Discharged volumes above 100 m^3 per 2 d within the municipality (2.0 log) were associated by elevated *E. coli* counts downstream. Similarly, *E. coli* counts above the intake closure threshold level at 400 CFU 100 mL^{-1} (2.6 log) were predominantly associated with higher discharge volumes. A weak positive trend was also found when comparing with additional microbial samplings taken within Ale municipality at Södra Nol monitoring station (Figure 5(A)). However, microbial contamination further upstream than Ale may contribute to the scattered pattern observed in the figure.

In Figure 5(B) the correlation between the local precipitation in Ale municipality and downstream *E. coli* counts is illustrated. The weak linear regression confirms that local precipitation did not directly influence the *E. coli* concentrations downstream. After the most intensive rain event, 24.4 mm, registered on 20 September at the weather station in Ale, *E. coli* counts of 570 CFU 100 mL^{-1} (2.75 log) were observed at the intake on 23 September.

DISCUSSION

Closure events due to the management of the source water intake regulation for the Göteborg drinking water supply

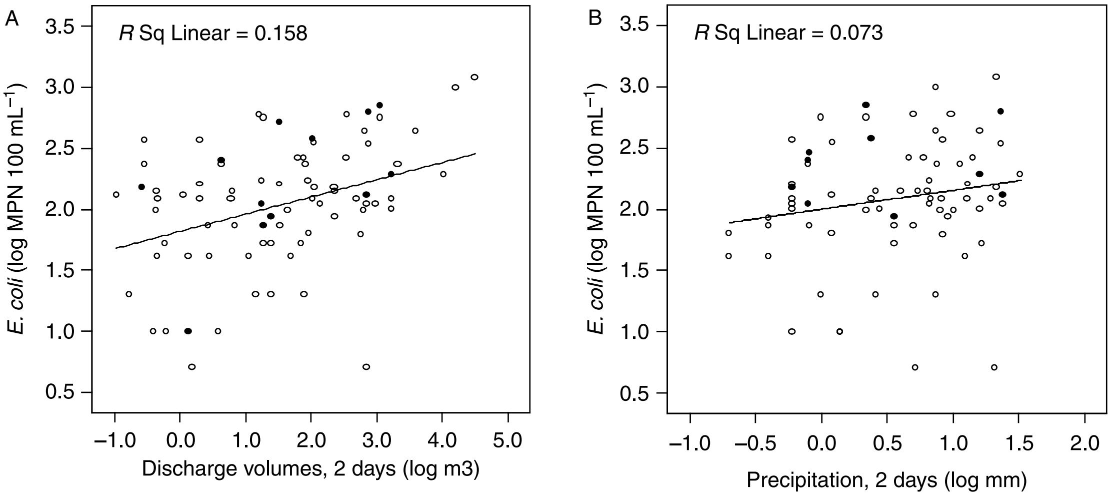

Figure 5 | The log/log correlations between (A) discharge volumes (m^3 during 2 d) in Ale municipality and (B) precipitation closure events (mm during 2 d) with the levels of *E. coli* at monitoring stations in Södra Nol in Ale municipality (●) and at the raw water intake for Göteborg (○). Data are from the second half of 2004 and the linear regression indicate the correlation.

system have been evaluated in relation to the variation of faecal indicator bacteria during a four-year study period. The periods of closed intake due to suspected or characterized microbial events generally corresponded to higher indicator counts at the intake compared to periods with non-microbial events and periods with open intake. Present results indicate that the intake management represent a microbial barrier for the drinking water system in Göteborg with respect to bacteria indicator parameters in the river Göta älv. As an example, closures due to microbial registrations in the upstream samplings excluded raw water with high total coliform levels from being used; a maximum of 17,000 units $100\,\mathrm{mL}^{-1}$ of total coliforms were removed by this management. Similarly, closures due to reports on wastewater discharges and rainfall removed high counts of *E. coli* and intestinal enterococci, indicating that microbial contaminations of the raw water used during these events were effectively prevented. The microbial risk reduction by the water intake management has been separately investigated with respect to the pathogens *Giardia*, *Cryptosporidium*, noro- and enteroviruses (Åström *et al.* 2007). This confirms that the intake closures are not effective only with respect to indicator bacteria but also represent a microbial barrier that gives a risk reduction due to these pathogens.

As stated, the closure management of the river intake provide a microbial barrier, which is presently regulated from online monitoring of indicator bacteria and upstream reports. However, the success in the exclusion of microbially contaminated river water is influenced by several factors. For example, the exactness within the present reporting system for upstream microbial events and the river transport time of pathogens may vary highly, which is further complicated by rapid flow regulations by the power plants within the river. As faecal indicators are normally used for monitoring of microbial contaminations the actual pathogen concentrations during event and non-event periods is largely unknown. Even though different bacteria indicators may complement each other, the indicator monitoring may result in misleading conclusions regarding the actual microbial risk. As an example, the survival in the environment often differs widely as comparing indicators and pathogens. Medema *et al.* (1997) reported *Cryptosporidium* oocysts and sulfite-reducing clostridia to be able to survive for several months in surface water, where a ten times higher decay rate was found for *E. coli* and for enterococci.

In the present study, high counts of all indicator bacteria were, on some occasions, also observed during periods with open water intake. Wastewater discharges from sewer overflows in the northern part of the river (Lilla Edet and upstream) are, in general, not reported to the Göteborg water treatment plant, obviously disabling closure of the raw water intake. Contaminations from these parts of the river may therefore contribute to high microbial counts, such as for the highly resistant clostridia, during periods of open intake. Occurrence of the sulfite-reducing clostridia, in the present results observed to be highly correlated with the turbidity, has in other studies been shown to indicate the pathogen variability in source waters (Payment & Franco 1993; Ferguson *et al.* 1996). As the flow time in Göta älv from Lake Vänern to the sea is estimated to be at a maximum of 5 d, the highly persistent sulfite-reducing clostridia may have a value as indicators of persistent pathogens spread upstream in the entire river.

From the microbial correlation with wastewater discharges and precipitation in the upstream Ale municipality, the positive trend with respect to the *E. coli* concentration was observed to be weak. In addition to the variability set by the transport time in the river, this result may reflect that microbial sources further upstream may influence the microbial load at the water intake. Influences from multiple sources have been reported from other studies on surface waters. For example, Obiri-Danso & Jones (1999) reported elevated levels of faecal coliforms, faecal streptococci and *Campylobacter* originating from various sources, such as a treated wastewater, agricultural runoff, streams and mallards. The Pearson's correlations analyses undertaken in the present study indicated a relationship between upstream precipitation, high turbidity and the microbial load. Elevated microbial impacts during heavy rains and surface runoffs are, in general, well reported within the literature, confirming the present results (Kistemann *et al.* 2002; Ferguson *et al.* 2003; Signor *et al.* 2005). Studies on statistics for waterborne outbreaks have shown significant positive correlations with extreme rain events (Rose *et al.* 2000; Curriero *et al.* 2001), which may be the result when pathogen spread often are associated with precipitation not effectively handled within the wastewater network.

Wastewater contamination of raw water sources, in combination with disinfection deficiencies, is reported as a common cause for water outbreaks in Nordic countries (Stenström *et al.* 1994; Andersson & Bohan 2001). The indicators bacteria evaluated in the present study, including total coliforms, *E. coli*, enterococci and clostridia, are often reported at similar levels in human and animal sewage, in the range 5–7.6 log CFU 100 mL^{-1} (Blanch *et al.* 2004). In Sweden, most of the water treatment plants include a secondary treatment (mechanical, chemical and biological treatment) which typically removes 99.9% of faecal coliform bacteria, but with a lower efficiency with respect to bacteriophages and virus particles (Stenström 1986; Ottoson *et al.* 2006). Wastewater discharges generally contain high loads of pathogens, and the parasitic protozoan *Giardia* and *Cryptosporidium* have been found in significant levels in wastewater treatment plants discharging to Göta älv (Ottoson 2001). In addition to wastewater, the microbial load in Göta älv is also influenced from stormwater discharges. Concentrations of *E. coli* in stormwater have been reported in the range of 1000–10,000 per 100 mL (Marsalek & Rochfort 2004), which corresponds well to local sampling data from Göteborg (Lavieille 2005).

Other sources of microbial contamination include livestock and industries, which are also represented in the Göta älv catchment. Faecal pathogens from animals, presenting a risk for zoonoses, may emanate from livestock areas (including farms) located in the catchment and which are highly represented around Lake Vänern (SCB 2003). Infective agents among livestock include *Giardia*, *Cryptosporidium*, *Campylobacter* and EHEC. Crowther *et al.* (2003) observed that large rural catchments including livestock areas may contribute substantially to high loads of faecal indicator bacteria in coastal waters. In the present investigation, the risk represented by livestock was exemplified by the single accident of manure spread in 2001, where the indicator bacteria levels were kept low in the used raw water thanks to effective reporting and effective actions by the farmer responsible for this accident. The microbial spread from industries was represented by discharges of paper mill effluents, reported as the trigger for 14 closures during the investigated period. In previous years, extensive spread of *Klebsiella* has been observed within Göta älv (Kühn *et al.* 1997; Stenström & Kühn 1988), however not of health significance as related to discharges from paper mills and not to the spread of human pathogens.

In Göteborg, the political aims include bathing places at the outflow from the river which are presently not possible due to the high counts of indicator bacteria in Göta älv (Rådmark *et al.* 2005). For bathing waters, a causal dose-related relationship between gastrointestinal symptoms and bacterial indicator counts have been shown in several epidemiological studies, reviewed by Prüss (1998). The interest in lowering the microbial load is therefore not only related to microbial risks within drinking water but also to the potential risks for exposures associated with recreational activities.

CONCLUSIONS

From this study we mainly conclude that raw water intake regulations may create a microbial barrier for drinking water in relation to different types of microbial contaminations upstream within a river catchment. As related to different types of microbial and non-microbial contaminations in Göta älv this intake management was shown to be effective with respect to selected indicator bacteria, mainly due to the microbial monitoring system and reporting systems. Separate samples taken during periods with open intake, however, also included high bacteria counts, potentially representing pathogen peaks, which indicate a weakness in this microbial barrier. High indicator bacteria counts during periods of open intake may reflect a risk for persistent pathogens, potentially spread from remote parts of the catchment. The positive correlation with microbial indicator bacteria concentrations suggests that the turbidity and the upstream accumulated precipitation should be promoted as complementary monitoring tools for the intake management of microbial spread within Göta älv.

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