Hydrodynamic modelling of the influence of stormwater and combined sewer overflows on receiving water quality: Benzo(a)pyrene and copper risks to recreational water

Preprint version. Accepted paper: https://doi.org/10.1016/j.jenvman.2017.11.014

This is a pre-print version of the paper

Hydrodynamic modelling of the influence of stormwater and combined sewer overflows on receiving water quality: Benzo(a)pyrene and copper risks to recreational water

The accepted manuscript was published in Journal of Environmental Management in February 2018.

Full citation: Björklund K, Bondelind M, Karlsson A, Karlsson D and Sokolova E (2018) Hydrodynamic modelling of the influence of stormwater and combined sewer overflows on receiving water quality: Benzo(a)pyrene and copper risks to recreational water. Journal of Environmental Management, 207, 32-42. DOI: 10.1016/j.jenvman.2017.11.014.

https://doi.org/10.1016/j.jenvman.2017.11.014

Preprint version. Accepted paper: https://doi.org/10.1016/j.jenvman.2017.11.014

Hydrodynamic modelling of the influence of stormwater and combined sewer overflows on receiving water quality: benzo(a)pyrene and copper risks to recreational water

K. Björklund[1], M. Bondelind[1], A. Karlsson[2], D. Karlsson[3] and E. Sokolova[1]*

[1] Department of Architecture and Civil Engineering, Chalmers University of Technology, Sven Hultins gata 8, SE-412 96 Gothenburg, Sweden

2 Tyréns AB, Lilla Badhusgatan 2, SE-411 21 Gothenburg, Sweden

3 Sustainable Waste and Water, City of Gothenburg, Box 123, SE-424 23 Angered, Sweden

*Corresponding author, email: ekaterina.sokolova@chalmers.se

Abstract

The risk from chemical substances in surface waters is often increased during wet weather, due to surface runoff, combined sewer overflows (CSOs) and erosion of contaminated land. There are strong incentives to improve the quality of surface waters affected by human activities, not only from ecotoxicity and ecosystem health perspectives, but also for drinking water and recreational purposes. The aim of this study is to investigate the influence of urban stormwater discharges and CSOs on receiving water in the context of chemical risks and recreational water quality. Transport of copper (Cu) and benzo[a]pyrene (BaP) in the Göta River (Sweden) was simulated using a hydrodynamic model. Within the 16 km modelled section, 35 CSO and 16 urban stormwater point discharges, as well as the effluent from a major wastewater treatment plant, were included. Pollutant concentrations in the river were simulated for two rain events and investigated at 13 suggested bathing sites. The simulations indicate that water quality guideline values for Cu are exceeded at several sites, and that stormwater discharges generally give rise to higher Cu and BaP concentrations than CSOs. Due to the location of point discharges and the river current inhibiting lateral mixing, the north shore of the river is better suited for bathing. Peak concentrations have a short duration; increased concentrations of the pollutants may however be present for several days after a rain event. Monitoring of river water quality indicates that simulated Cu and BaP concentrations are in the same order of magnitude as measured concentrations. It is concluded that hydrodynamic modelling is a useful tool for identifying suitable bathing sites in urban surface waters and areas of concern where mitigation measures should be implemented to improve water quality.

Keywords

Chemical risks; hydrodynamic modeling; recreational water quality; urban runoff; wastewater.

Preprint version. Accepted paper: https://doi.org/10.1016/j.jenvman.2017.11.014

1 Introduction

Surface waters in close proximity to urban areas are recipients of liquid waste streams such as urban runoff, domestic and industrial wastewater. Industrial wastewater may pose both chemical and physical stresses on receiving water quality depending on the industrial activity, e.g. food processing, mining, pulp and paper (Ali and Sreekrishnan 2001, Dudka and Adriano 1997, Lefebvre and Moletta 2006, Pokhrel and Viraraghavan 2004). Both treated and raw domestic wastewater are major sources of nutrients and microbial contamination in receiving waters (Henze et al. 2008). Also, greywater (no faecal contamination, e.g. kitchen, shower and laundry wastewater) carries pollutants for which the wastewater treatment processes are not optimised (Luo et al. 2014): metals such as copper, zinc, lead and chromium and xenobiotic organic compounds, e.g. pharmaceuticals, detergents and personal care products (Eriksson 2002, Paxeus and Friedrich Schroder 1996, Sörme and Lagerkvist 2002). Surface runoff from urban areas is an important sink for metals, petroleum hydrocarbons and other organic compounds emitted from human activities including commerce, construction and transportation (Kayhanian et al. 2007, Makepeace et al. 1995, Zgheib et al. 2012). Traffic has been identified as one of the major causes of runoff pollution, often giving rise to alarming levels of metals, e.g. copper, lead and zinc emitted with fuels, vehicle- and road-related wear, and hydrocarbons derived from petroleum products and combustion, e.g. polycyclic aromatic hydrocarbons (PAHs), alkanes and alkenes (Markiewicz et al. 2017, Opher and Friedler 2010).

The risk from chemical substances in surface waters is often increased during wet weather, due to surface runoff, sewer overflows and erosion of contaminated land. Stormwater management, i.e. source control and regional on-site treatment of polluted runoff, is considered necessary to achieve set water quality standards, such as the EU Water Framework Directive (European Commission 2000). There are strong incentives to improve the water quality of surface waters affected by human activities, not only from ecotoxicity and ecosystem health perspectives, but also because many surface waters are used for drinking water production and recreational purposes. Restoration of urban rivers and lakes, e.g. through flood control, stormwater treatment and increase of riparian vegetation and habitat complexity, can lead to a more positive image of urban waterways, raise the quality of life in urban areas and provide space for recreation (EEA 2016). One successful example is Copenhagen in Denmark, where implementation of reservoirs and reservoir conduits for water storage during wet weather has resulted in the closing of 55 overflow channels and substantially reduced wastewater discharges to the harbour. There are currently five public harbour bathing sites in Copenhagen, and many more European cities are aiming at providing safe recreational bathing for their residents.

The city of Gothenburg in Sweden has a vision that by 2021, there should be extended possibilities to swim in, or in direct proximity to, the Göta River in the central parts of the city (Göteborg Stad 2013). The complexity lies in the Göta River being a waterway with both known and diffuse emission sources of physical, biological and chemical stressors. Various industrial and commercial activities have been and are still active along the Göta River, and the river is an important transportation route for both commercial and recreational boat traffic. The major inputs to the river are cooling water from industries and discharges of treated domestic wastewater (corresponding to approximately 900,000 PE) and untreated wastewater released at combined sewer overflows (CSOs). Stormwater from six municipalities is also discharged to the river, where the city of Gothenburg is assumed to be the largest source of both runoff volumes and pollutant loads due to its size.

The impact of pollutant loads on the receiving water can be assessed by means of water quality modelling, which is a useful approach to inform mitigation, management and regulations. The fate and transport of pollutants within the water source can be simulated using hydrodynamic modelling. This type of modelling has been widely applied to assess the impact of stormwater and wastewater discharges on the microbial water quality in the water sources used for drinking water supply, shellfish harvesting, and recreation (De Brauwere et al. 2014). In this context, hydrodynamic modelling has been used to describe the temporal and spatial variability of pollutant concentrations (e.g. Eregno et al. 2016, Hoyer et al. 2015), to understand the importance of different factors influencing the pollutant fate and transport (e.g. Liu et al. 2015), and to quantify the relative impact of different sources (e.g. Dienus et al. 2016). In addition, this approach can complement monitoring and to some extent address the limitations of analytical methods, such as cost, temporal resolution, and detection limits.

The aim of this study was to investigate the influence of urban stormwater discharges and CSOs on receiving water in the context of chemical risks and recreational water quality by simulating the transport of copper (Cu) and benzo[a]pyrene (BaP) in the Göta River using a hydrodynamic model. The specific objectives of the study were to: i) estimate the annual loads of Cu and BaP to the Göta River from major sources in the city of Gothenburg, including stormwater, CSOs and wastewater treatment plant discharges; ii) identify suitable bathing sites along the Göta River in the central areas of Gothenburg; iii) investigate the duration of the negative impact on recreational water quality posed by stormwater and CSO discharges into the Göta River; and iv) identify areas of concern where mitigation measures should be implemented to improve the Göta River water quality with respect to recreational use.

2 Method

2.1 Study area

Göta River is the largest river in Sweden, draining a 50 000 km^2 catchment area into Kattegat strait on the West coast of Sweden. The river is used for drinking water production, transportation, hydropower production, fish farming and sport fishing. The water flow in the river is regulated by several hydropower stations. Located at the mouth of the river is Gothenburg, the region’s largest and Sweden’s second largest city, with approximately 550 000 residents.

Long-term monitoring of the Göta River water quality shows that discharges upstream of Gothenburg city centre do not give rise to alarming levels of metals and organic pollutants, which are all below water quality standards (unpublished data). However, the river water quality in the central parts of Gothenburg, where recreational water activities are planned and where stormwater and sewer overflows are likely to affect water quality, has not been monitored. Thus it is not known whether there are any chemical risks at the 13 proposed locations for bathing sites along the river (Figure 1).

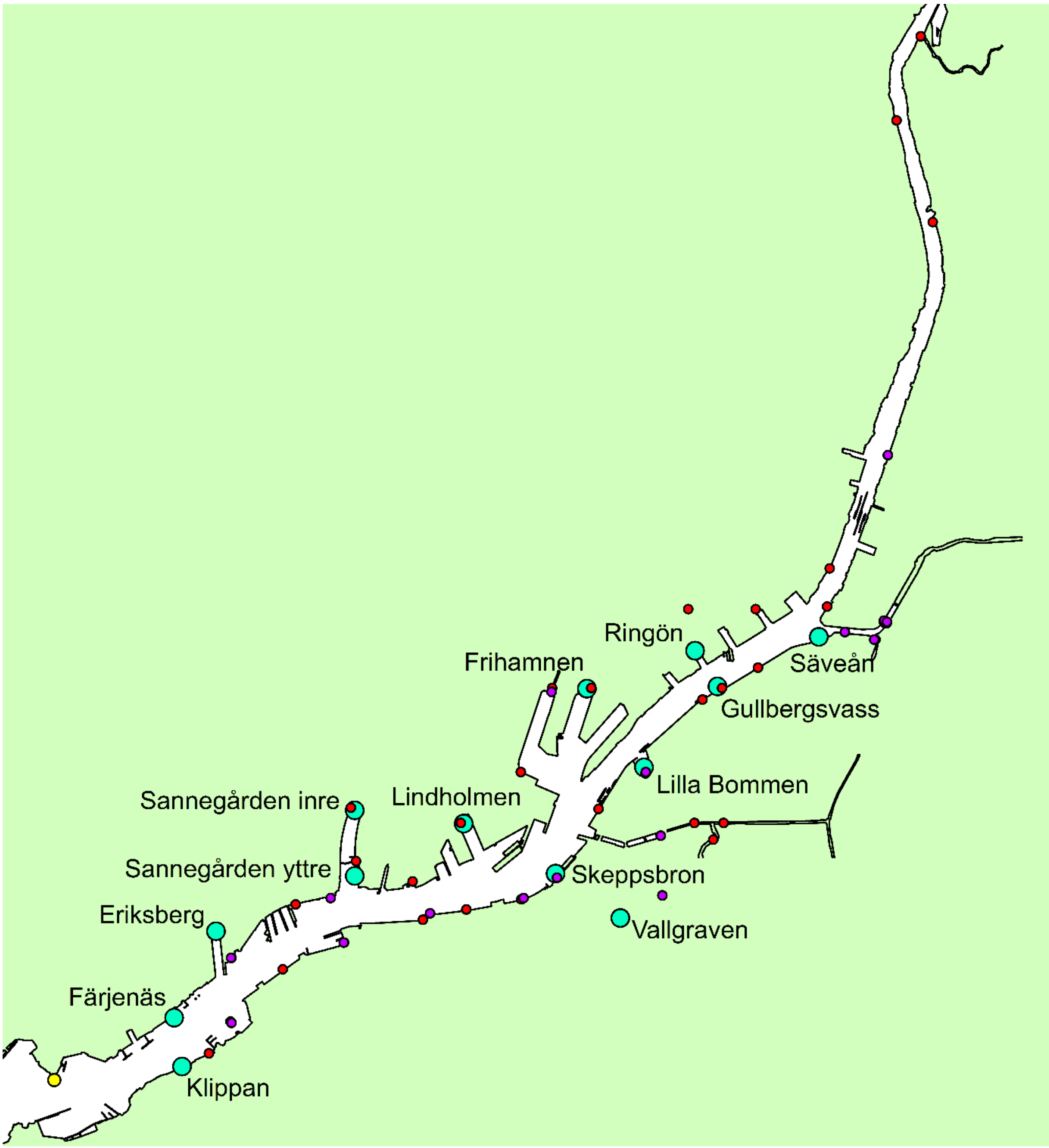


Figure 1. *Map showing the modelled section of the Göta River with suggested bathing sites (green dots). Discharge points of stormwater (red), CSOs (purple) and Rya WWTP (yellow) are further described in Supporting Information.*

In this study, we focus on the 16 km stretch of the river, from Lärjeholm in the north to Älvsborg old fort in the southwest, encompassing all proposed bathing sites (Figure 1). All major freshwater tributaries that may influence the river water quality within the model area, are described in the model.

Flows from both CSOs and stormwater runoff have been included in the model. Within the study area, CSOs annually contribute with 215 000 m^3 domestic wastewater to the river. Runoff from 2300 ha impervious areas in the city of Gothenburg is drained into the Göta River and its tributaries covered by the model, giving rise to an annual discharge of 14 Mm^3 stormwater to the river. At Rya WWTP, approximately 130–140 Mm^3 raw wastewater annually pass through mechanical, chemical and biological treatment processes, before being discharged at 2–3 m depth at the mouth of the river. Discharges of wastewater due to operational failure (7000 m^3 in 2015) were not included in the model, as they may appear at any time and are not related to precipitation and runoff. For the same reason, incidental discharges such as erosion and spills were not considered in the model.

2.2 Pollutants

An inorganic element, copper (Cu), and an organic pollutant, benzo[a]pyrene (BaP) – a high molecular weight PAH, were included in this study. Both Cu and BaP are relevant from a water management point of view, as they are frequently detected in urban runoff at concentrations exceeding national and international water quality standards (Gasperi et al. 2014, Zgheib et al. 2012). In addition, BaP and Cu are regulated through the Swedish drinking water directive and stormwater quality standards set by the environmental administration in Gothenburg (Livsmedelsverket 2015, Miljöförvaltningen Göteborg Stad 2013). Guideline concentrations of BaP, and other PAHs, in marine and freshwater are also specified in the European Water Framework Directive and the Canadian Environmental Quality Guidelines (CCME 2011, European Commission 2001). Recreational and bathing water quality guidelines from around the world are limited to microbial risks (Health Canada 2012, US EPA 2012, WHO 2003), whereas risks associated with toxic chemicals are currently not considered. Hence chemical parameters are rarely monitored for surface waters used for recreation.

Benzo[a]pyrene, as well as other PAHs, is emitted during combustion of organic material, e.g. waste incineration, wood burning and vehicle exhaust, as well as from tyre rubber and other petroleum products (Markiewicz et al. 2017, Ravindra et al. 2008). Major sources of Cu in urban runoff include vehicle brake pads and roofing. Also, drinking water pipes are often made of Cu, hence wastewater and CSOs are important Cu sources (Sörme and Lagerkvist 2002). Both Cu and BaP exert negative effects on human and animal health, including neurotoxicity (Cu) and carcinogenicity (BaP) (International Agency for Research on Cancer 2012, Pal et al. 2014).

Approximately 60 and 80 % of Cu and BaP, respectively, can be expected in the non-dissolved phases of stormwater, although large partition variations exist (Brown 2002, Camponelli et al. 2010, Maniquiz-Redillas and Kim 2014, Nielsen et al. 2015, Prestes et al. 2006, StormTac corporation 2016, WERF 2016). Generally, the highest loads of both BaP and Cu are found in the fine particle fractions (< 30 µm) (Herngren et al. 2010, Nielsen 2015, Sansalone et al. 1998, WERF 2016). In this study, we assume no degradation as BaP $t_{1/2}$ > 42 days (CCME 1999), and that no settling of pollutants bound to fine particles occurs in the river, i.e. a worst-case scenario. Large particles and thereto bound pollutants are assumed to be trapped while transported to or in the sewer system, for example in road side sediment, gully pots and sediment traps.

2.3 Water quality modelling

To study the influence of stormwater discharges and CSOs on the water quality at the suggested bathing sites, a three-dimensional hydrodynamic model was set up using MIKE 3 FM (MIKE Powered by DHI) software. The modelling domain was described using a flexible computational mesh: resolution 20–30 m in the horizontal and 1 m in the vertical direction. Input data to the model included water flows in the river and its tributaries, water level and salinity stratification in the Kattegat strait, and meteorological conditions. The data were obtained from the Swedish Meteorological and Hydrological Institute and the city of Gothenburg.

Discharges of wastewater upstream the city of Gothenburg were not included in this study, as the main focus was to identify the impact of the sources within the city. River entry points for stormwater discharges and CSOs, respectively, have been lumped together to decrease the complexity of the model. Included in the model of the Göta River are 35 points from separate stormwater sewers and 16 points of discharge from combined sewers, as well as the effluent from the Rya WWTP (Figure 1 and Supporting Information). The time-series for CSOs and stormwater discharges into the river and its tributaries were created based on observations and modelling by the city of Gothenburg. Discharge points were added to the surface of the model, although some may in reality emerge below the water surface, because the released (fresh) water is lighter than the river (brackish) water and will rise to the surface.

For each point of discharge, median and maximum concentrations of Cu and BaP were identified, representing a general (median) and a worst-case scenario. Concentrations in the WWTP effluent and CSOs were collected from reports published by the WWTP owner. For stormwater, the area drained to each specific point of discharge was identified with respect to land use (e.g. type of housing if any, industrial activity, green areas, roads) and annual average daily traffic (AADT) (City of Gothenburg 2017). Stormwater concentrations of Cu and BaP for each land use type were retrieved from the StormTac database (StormTac corporation 2016). In areas of mixed land use, the pollutant concentrations were approximated from represented area types and their contribution to the total area. Derived pollutant concentrations from each entry point are presented in the Supporting Information.

In order to study the influence of wastewater and stormwater discharges on the water quality at the suggested bathing areas, two periods during 2015 were selected: 5 – 13 July (period 1) and 24 July – 1 August (period 2). The water flow in the river varied between 65 and 166 with a mean of 138 m^3/s and between 115 and 186 with a mean of 178 m^3/s during periods 1 and 2, respectively. The total precipitation was 27 and 57 mm during periods 1 and 2, respectively. Precipitation occurred during one rain event for period 1 and during two rain events for period 2.

2.4 Water quality monitoring

On 29 August September 2016, river water was grab sampled close to discharge points TS6 (57°42’09.1”N 11°57’05.5”E) and TS9/GÄ16 (57°42’23.7”N 11°57’24.3”E) (see Supporting Information). The water samples were analysed for total Cu and BaP concentrations. Sampling was timed with a rainfall event, and water was collected from the two sites once prior to the rain event and then approximately once per hour after the event ($n = 9$). Data from the Swedish Meteorological and Hydrological Institute (gauge located at 57°42’56.4”N 11°59’33.0”E) indicate 20.2 mm rain 24 h prior to sampling (27–28 September) and 10.0 mm on 29 September, with most rain falling between 02:00 and 10:00 (approximately corresponding to 1-month rainfall return period (Dahlström 2006)), whereas most samples were collected after 08:00 (for practical reasons).

2.5 Statistical analyses

The program IBM SPSS Statistics 22 was employed to perform statistical analyses. The Mann-Whitney U (two groups) and Kruskal-Wallis (more than two groups) tests were used to compare differences between independent groups when data were not normally distributed. Normality was tested using the Shapiro-Wilk test: if $p > 0.05$, the distribution of data is not significantly different from a normal distribution.

3 Results and discussion

3.1 Annual loads of Cu and BaP entering the Göta River

The median and maximum annual loads of Cu and BaP in the city of Gothenburg are shown in Table 1. Within the city, stormwater contributes with almost three times as much Cu and almost five times as much BaP than CSOs. If compared to the background pollution from natural and anthropogenic sources upstream the city of Gothenburg, the load of Cu from stormwater and CSOs within the city is considerably lower. The combined Cu load from stormwater and CSOs is in the same range as the median annual discharge from the WWTP, although the estimated maximum discharge is substantially larger from the WWTP. Annual discharges of BaP within the city is higher than the discharges from the WWTP. Discharges from the WWTP enter the river downstream from the city and do not influence any of the suggested bathing sites.

Table 1. *Estimated annual loads of copper (Cu) and benzo(a)pyrene (BaP) into the Göta River from sources upstream the city of Gothenburg (background), and sources in the city of Gothenburg including stormwater discharges, combined sewer overflows (CSOs) and Rya wastewater treatment plant (WWTP). The median and maximum values were calculated based on the assumed concentrations at the pollution sources (stormwater, CSOs, WWTP) and minimum and maximum monitored concentrations in the river (background). The BaP load from background sources could not be calculated due to lack of monitoring data.*

	Cu median, kg/year	Cu max, kg/year	BaP median, g/year	BaP max, g/year
Background	6600	7200	No data	No data
Stormwater	740	1100	1100	1600
CSOs	210	490	230	370
WWTP	920	6700	660	740

The annual loads of Cu and BaP from stormwater and CSOs at discharge points along the river are shown in Figure 2. When all discharge points are considered, the highest loads of Cu and BaP originate from GÄ1 (Bäckebol), Mölndalsån and Lärjeån (Figure 2, Supporting Information). Among the CSOs, the highest loads of Cu and BaP originate from TS2c (Gamlestan-Munkebäck) and TS4 (Kvillebäcken). Among the stormwater discharges entering the river directly (and not through the tributaries), the highest loads of Cu originate from GÄ1 (Bäckebol) and GÄ14 (Järntorget), and the highest loads of BaP originate from GÄ14 (Bäckebol) and GÄ2 (Alelyckan).

The high values of Cu in wastewater originate primarily from pipe leaching in the drinking water network (Sörme and Lagerkvist 2002), although food scraps and stormwater from the combined sewer network (approximately 35 % of the sewers in Gothenburg) also contribute to the Cu loads from the WWTP. In fact, WWTP discharges and CSOs often exhibit higher Cu concentrations than detected in urban stormwater, unless the drained surface areas is highly affected by traffic sources (Ahlman et al. 2004, Davidsson and Mattsson 2013, StormTac corporation 2016). Traffic is the primary source of both PAHs and metals in stormwater, and the identified major discharge sources all have in common that they drain large roads (Figure 2). Both Mölndalsån and Gamlestan-Munkebäck (TS2c) receive runoff from some of the most traffic-affected areas in the city of Gothenburg (50,000 to 120,000 AADT). Further, Bäckebol (GÄ1) and Alelyckan (GÄ2) drain industrial areas and highways with approximately 50,000 (E6 motorway) and 25,000 AADT (local traffic), respectively, and Järntorget (GÄ14) is a hub with both local and regional traffic (approximately

20,000 AADT). The discharge point Lärjeån is an exception as it drains residential areas resulting in lower Cu and BaP stormwater concentrations (StormTac corporation 2016). However, the water volume from this area is very large (approximately 2000 Mm^3), resulting in high Cu and BaP loads. From a pollutant load perspective, it is advisable not to locate any bathing sites in the northern parts of the city, upstream from the downtown core, since this is where runoff from major roads and highways is discharged into the Göta River. However, pollutants are swiftly transported downstream both as dissolved constituents and with deposited sediments.

Preprint version. Accepted paper: https://doi.org/10.1016/j.jenvman.2017.11.014

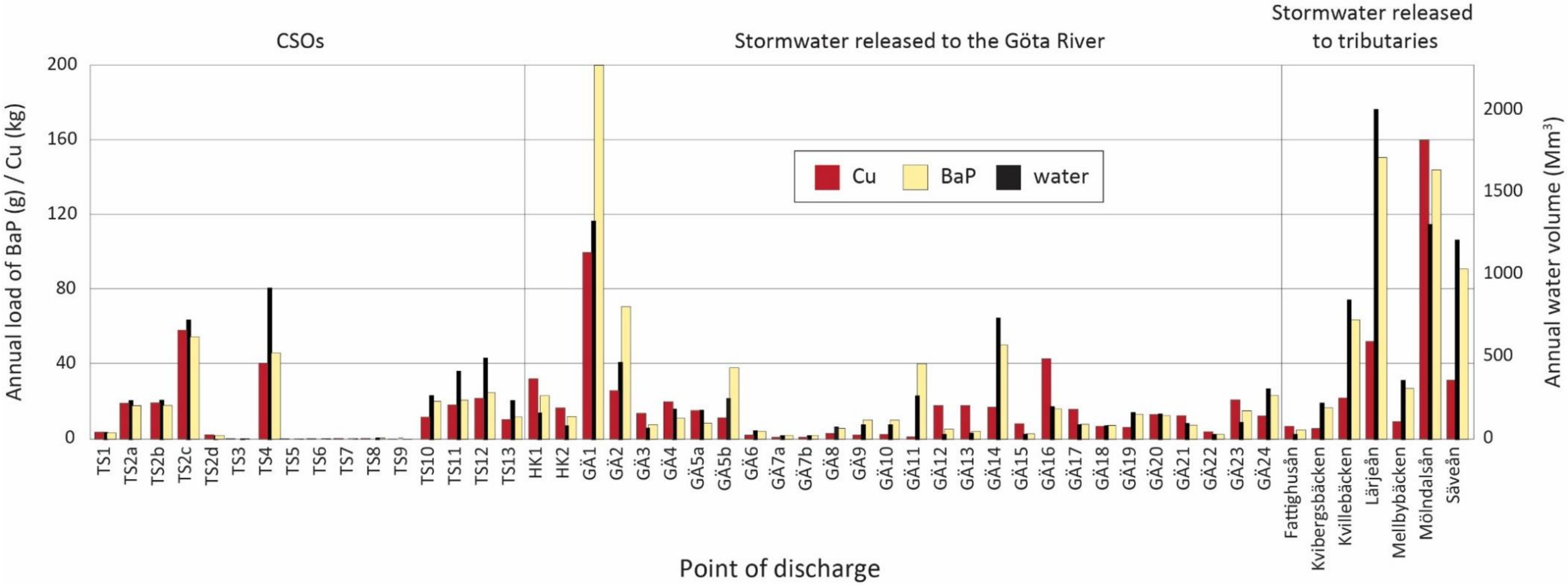


Figure 2. *Annual released loads of Cu (red, kg/year) and BaP (yellow, g/year) and water volumes (black, m^3/year) to the Göta River from each point of discharge (more details on discharge points are found in the Supporting Information).*

3.2 Simulated concentrations of Cu and BaP in the Göta River

The concentrations of Cu and BaP at the suggested bathing sites during precipitation were modelled for two periods (period 1 and 2). Table 2 presents the highest concentrations of Cu and BaP, caused by stormwater and CSOs, at each of the proposed bathing sites. The modelling results show that at some sites, the concentrations exceed stormwater and receiving waters guideline values established by the city of Gothenburg (10 and 0.05 µg/L for Cu and BaP, respectively, no available guidelines for recreational waters). Stormwater caused significantly higher (Mann-Whitney *U* test, $p < 0.05$, 2-tailed) concentrations of Cu and BaP (both maximum and median values) than CSO discharges during period 1, but only higher BaP concentrations during period 2. Due to the river flow and resulting velocity field, discharges from the WWTP do not affect water quality at any of the suggested bathing sites.

Higher pollutant concentrations along the south shore of the river is visible in Figure 3. Statistical testing reveals that the bathing sites on the north shore of the river (Figure 1, Table 2) are exposed to significantly lower Cu concentrations (Mann-Whitney *U* test, $p < 0.05$, 2-tailed) from both stormwater and CSO discharges during both simulated periods, with Cu stormwater median values being an exception. The BaP concentrations are also generally lower along the north shore, but the difference is statistically significant only for CSO discharges. Consequently, discharges on the south shore of the river appear not to affect the north shore.

The higher concentrations for period 2 compared to period 1 (Table 2) were mainly caused by more precipitation: a larger volume of stormwater and wastewater discharged into the river cause a higher load of pollutants to enter the river. Variations between the concentrations when maximum and median values are used, are to some extent caused by a smaller or larger span of values used (Supporting Information).

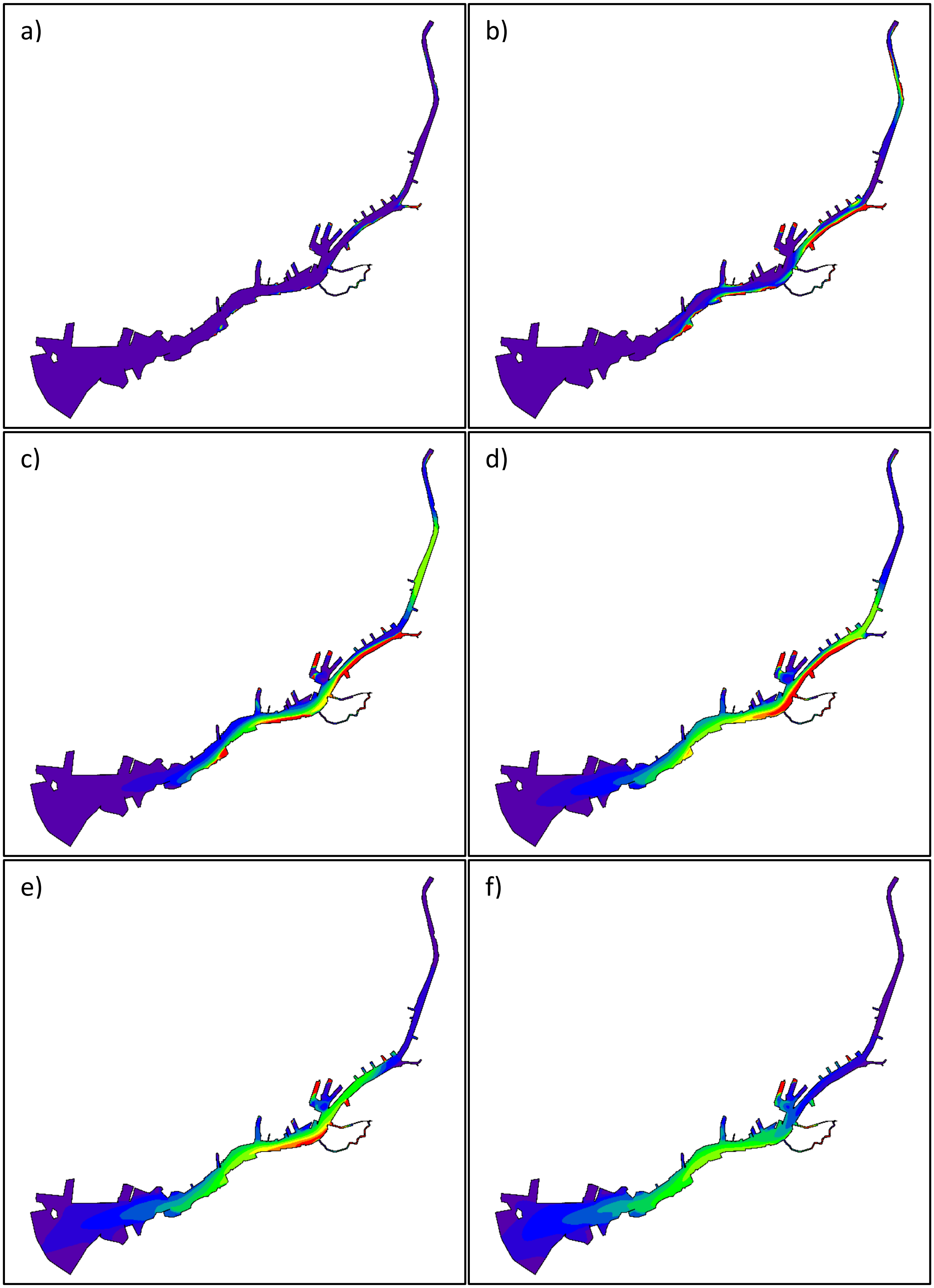

a)
b)
c)
d)
e)
f)

Figure 3. *Simulated concentrations of Cu in the Göta River resulting from stormwater discharges on a) 28 July at 17:00, b) 28 July at 19:00, c) 28 July at 21:00, d) 28 July at 23:00, e) 29 July at 01:00, f) 29 July at 03:00. Purple and red colours represent concentrations 0 and >2 [μg/L], respectively. The maximum estimations of concentrations at sources were used as input data in the model.*

The Cu concentrations exceed the guideline values at the following suggested sites: Vallgraven, Frihamnen, Gullbergsvass and Säveån (Figure 1, Table 2). The BaP concentration only exceeds the guideline value once for simulated period 2 at Frihamnen and is close to the guideline value at Vallgraven. If either of these sites would be chosen for public bathing, extensive mitigation measures would have to be put in place to lower the Cu and BaP concentrations.

The suggested bathing sites Vallgraven and Frihamnen are affected mostly by local sources, since mixing with river water is limited compared to other sites (Figures 1 and 3). Vallgraven is located in the highly impervious downtown core of Gothenburg. It receives large volumes of stormwater and CSOs compared to its base flow, and water circulation is slow, leading to considerable impact from stormwater and CSO discharges during wet weather (Ahlman et al. 2004). In Frihamnen, mixed industrial, residential (single- to multi-family housing), traffic and commercial sources give rise to pollutants in both stormwater and CSOs. However, this area will undergo major transformation and exploitation within a near future, hence there is great potential to implement stormwater and CSO mitigation practices to improve the water quality (Tyréns AB 2016).

The suggested bathing sites Gullbergsvass and Säveån are, as opposed to Vallgraven and Frihamnen, affected by several upstream sources. Gullbergsvass is influenced by pollution from the rail road (Gothenburg Central Station and rail yard), highways (mainly E45, but also E6 and E20), freight forwarding and the main post sorting office, as well as upstream discharges from traffic and industrial areas. The Säveån suggested bathing site is influenced by discharges from traffic, industrial areas as well as large CSO discharges upstream, and is hence unsuitable for recreation use. The diffuse sources may be more difficult to identify and mitigate than local sources.

Suitable places for bathing, in terms of chemical risks, are Ringön and Eriksberg, which both exhibit low concentrations of Cu and BaP and are located on the north shore of the river. In terms of microbial water quality in the river, Sannegården inre, Sannegården yttre and Lindholmen may be more suitable for bathing (Tyréns AB 2016). These potential bathing sites (Sannegården inre, Sannegården yttre and Lindholmen) show low peak concentrations of Cu and BaP. The concentration of Cu varies over time, and at some locations, the pollutant may be present for a longer time (Figure 3). From Figure 4, it is clear that the peak concentrations have short duration, however, increased concentrations are present for several days. Sannegården yttre seems to be affected for a shorter time span (in period 1) by stormwater discharges, in comparison to the other two suggested bathing places (Figure 4). On the other hand, Sannegården yttre is affected to a larger extent by CSOs.

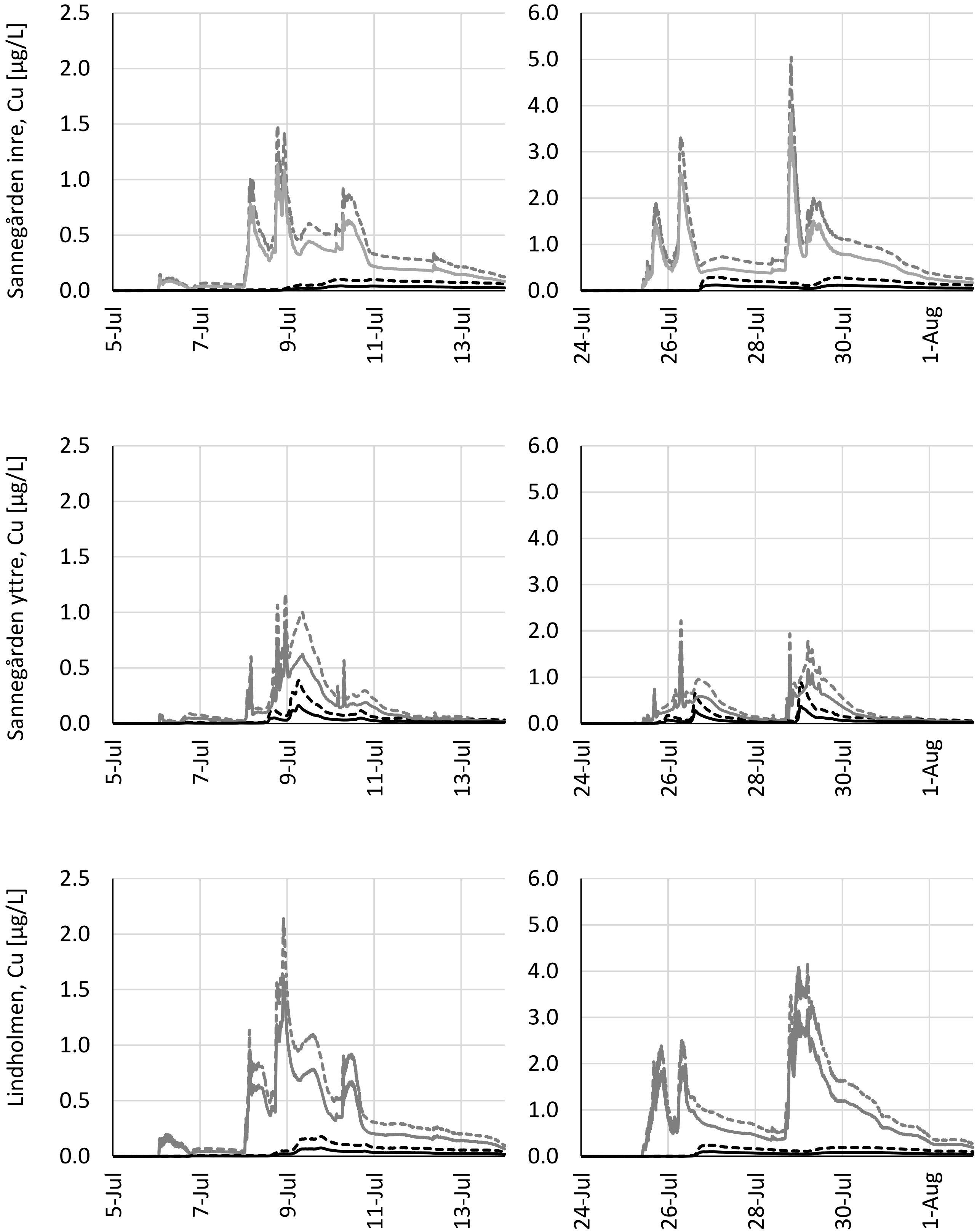

Sannegården inre, Cu [µg/L]
Sannegården yttre, Cu [µg/L]
Lindholmen, Cu [µg/L]
0.0
0.5
1.0
1.5
2.0
2.5
1.0
2.0
3.0
4.0
5.0
6.0
5-Jul
7-Jul
9-Jul
11-Jul
13-Jul
24-Jul
26-Jul
28-Jul
30-Jul
1-Aug

Figure 4. *Simulated concentrations of Cu at the proposed bathing sites: Sannegården yttre, Sannegården inre and Lindholmen. Black and grey lines represent the influence of CSOs and stormwater, respectively. Solid and dotted lines represent the results based on the median and maximum concentrations (estimated based on reported values) at the sources, respectively. The corresponding figure for BaP is presented in Supporting Information.*

Table 2. *Modelling results: concentrations (µg/L) of Cu and BaP caused by stormwater discharges (SW) and combined sewer overflows (CSO) at the proposed bathing sites in the river (see Figure 1). The two values represent the highest concentrations in the river when maximum and median (in parenthesis) estimations of concentrations at sources were used as input data in the model (see Supporting Information for concentrations).*

Preprint version. Accepted paper: https://doi.org/10.1016/j.jenvman.2017.11.014

	Period 1 (5 July – 13 July 2015)				Period 2 (24 July – 1 August 2015)			
Location name	**Cu SW**	**Cu CSO**	**BaP SW**	**BaP CSO**	**Cu SW**	**Cu CSO**	**BaP SW**	**BaP CSO**
Säveån	15.7	54.8	$1.49\cdot10^{-2}$	$2.87\cdot10^{-2}$	30.9	108	$2.92\cdot10^{-2}$	$5.68\cdot10^{-2}$
	(7.82)	(23.0)	($1.07\cdot10^{-2}$)	($2.15\cdot10^{-2}$)	(15.4)	(45.4)	($2.09\cdot10^{-2}$)	($4.26\cdot10^{-2}$)
Ringön	0.813	$5.36\cdot10^{-2}$	$1.58\cdot10^{-3}$	$2.80\cdot10^{-5}$	1.20	0.0910	$2.35\cdot10^{-3}$	$4.77\cdot10^{-5}$
	(0.571)	($2.25\cdot10^{-2}$)	($1.14\cdot10^{-3}$)	($2.10\cdot10^{-5}$)	(0.849)	(0.0381)	($1.72\cdot10^{-3}$)	($3.57\cdot10^{-5}$)
Gullbergsvass	4.85	9.30	$5.20\cdot10^{-3}$	$4.87\cdot10^{-3}$	8.56	24.7	$8.25\cdot10^{-3}$	$1.29\cdot10^{-2}$
	(2.60)	(3.90)	($3.72\cdot10^{-3}$)	($3.65\cdot10^{-3}$)	(4.31)	(10.4)	($5.91\cdot10^{-3}$)	($9.70\cdot10^{-3}$)
Lilla Bommen	3.95	2.70	$4.86\cdot10^{-3}$	$1.41\cdot10^{-3}$	5.99	7.70	$8.46\cdot10^{-3}$	$4.02\cdot10^{-3}$
	(2.66)	(1.14)	($2.92\cdot10^{-3}$)	($1.07\cdot10^{-3}$)	(4.92)	(3.23)	($4.40\cdot10^{-3}$)	($3.03\cdot10^{-3}$)
Frihamnen	13.3	0.148	$3.54\cdot10^{-2}$	$1.18\cdot10^{-4}$	24.1	0.320	$6.41\cdot10^{-2}$	$2.71\cdot10^{-4}$
	(7.59)	(0.0641)	($2.53\cdot10^{-2}$)	($6.46\cdot10^{-5}$)	(13.7)	(0.139)	($4.58\cdot10^{-2}$)	($1.44\cdot10^{-4}$)
Skeppsbron	2.20	1.74	$2.74\cdot10^{-3}$	$9.11\cdot10^{-4}$	4.03	5.56	$4.54\cdot10^{-3}$	$2.91\cdot10^{-3}$
	(1.26)	(0.823)	($1.93\cdot10^{-3}$)	($7.98\cdot10^{-4}$)	(2.15)	(2.78)	($3.22\cdot10^{-3}$)	($2.69\cdot10^{-3}$)
Vallgraven	19.1	1.69	$2.74\cdot10^{-2}$	$8.86\cdot10^{-4}$	33.6	25.6	$4.82\cdot10^{-2}$	$1.34\cdot10^{-2}$
	(16.8)	(0.913)	($1.22\cdot10^{-2}$)	($8.86\cdot10^{-4}$)	(29.5)	(13.8)	($2.14\cdot10^{-2}$)	($1.34\cdot10^{-2}$)
Lindholmen	2.14	0.178	$4.02\cdot10^{-3}$	$9.37\cdot10^{-5}$	4.15	0.236	$7.91\cdot10^{-3}$	$1.25\cdot10^{-4}$
	(1.62)	(0.0748)	($3.01\cdot10^{-3}$)	($6.91\cdot10^{-5}$)	(3.17)	(0.0989)	($5.92\cdot10^{-3}$)	($9.27\cdot10^{-5}$)
Sannegården	1.49	0.104	$2.84\cdot10^{-3}$	$5.35\cdot10^{-5}$	5.05	0.293	$9.54\cdot10^{-3}$	$1.54\cdot10^{-4}$
inre	(1.14)	(0.0436)	($2.13\cdot10^{-3}$)	($3.72\cdot10^{-5}$)	(3.83)	(0.123)	($7.14\cdot10^{-3}$)	($1.15\cdot10^{-4}$)
Sannegården	1.17	0.386	$2.14\cdot10^{-3}$	$2.00\cdot10^{-4}$	2.22	0.889	$4.11\cdot10^{-3}$	$4.67\cdot10^{-4}$
yttre	(0.863)	(0.162)	($1.59\cdot10^{-3}$)	($1.50\cdot10^{-4}$)	(1.66)	(0.373)	($3.07\cdot10^{-3}$)	($3.47\cdot10^{-4}$)
Eriksberg	0.193	0.307	$3.09\cdot10^{-4}$	$2.65\cdot10^{-4}$	0.411	0.824	$6.00\cdot10^{-4}$	$7.57\cdot10^{-4}$
	(0.130)	(0.134)	($2.24\cdot10^{-4}$)	($1.38\cdot10^{-4}$)	(0.265)	(0.360)	($4.31\cdot10^{-4}$)	($3.92\cdot10^{-4}$)
Färjenäs	1.17	1.28	$1.55\cdot10^{-3}$	$1.22\cdot10^{-3}$	1.77	3.71	$2.47\cdot10^{-3}$	$3.69\cdot10^{-3}$
	(0.697)	(0.559)	($1.11\cdot10^{-3}$)	($6.24\cdot10^{-3}$)	(1.00)	(1.63)	($1.77\cdot10^{-3}$)	($1.85\cdot10^{-3}$)
Klippan	1.65	0.973	$1.99\cdot10^{-3}$	$6.92\cdot10^{-4}$	3.80	2.06	$3.64\cdot10^{-3}$	$1.23\cdot10^{-3}$
	(1.10)	(0.417)	($1.42\cdot10^{-3}$)	($4.59\cdot10^{-4}$)	(2.81)	(0.874)	($2.89\cdot10^{-3}$)	($8.82\cdot10^{-4}$)

3.3 Validity of the modelling approach

The hydrodynamic model for the Göta River has been set -up in earlier studies and found adequate to describe the hydrodynamic situation in the river (Tyréns AB 2016). In this paper, changes to the model were the inclusion of Cu and BaP stormwater and CSO concentration data, which are subject to uncertainties. The Cu and BaP stormwater concentration data used in the model are based on summary statistics of reported values (StormTac corporation 2016). The used Cu concentrations were compared to data found in the American National Stormwater Quality Database (BaP not available) (University of Alabama 2015). In this database, land use definitions are less detailed than in StormTac and land use-specific Cu concentrations vary by three orders of magnitude. Hence using more land use-specific data from the StormTac database was considered more accurate.

For some land uses, e.g. residential and downtown area, the sample size in the StormTac database is very small ($n \leq 5$); data for BaP are generally scarcer than Cu data. Most discharge points (Figure 1) drain areas of mixed land use, Cu and BaP concentrations in stormwater from each point is estimated by combining reported concentrations for different land uses. Since the boundary of the catchment area to each discharge point is not known, the drained area and land use connected to each discharge point is a rough estimate. For the worst-case assumptions, the highest reported Cu and BaP concentrations for the included land uses were used, which were often found for roads. In the median cases, used Cu and BaP concentrations were an average of reported concentrations for included land uses. However, the reported concentrations of Cu in stormwater from different land uses are all within one order of magnitude (26–79 µg/L), the only exception is roads with ≥ 50,000 AADT which give rise to Cu concentrations over 100 µg/L (StormTac corporation 2016). Reported BaP concentrations are more varied, from 0.01 to 0.3 µg/L depending on land use. Very few CSO concentration data exist, although Cu concentrations used in the model were collected from measurements performed in Gothenburg (Davidsson and Mattsson 2013). Used concentrations of Cu and BaP in stormwater and CSO are indeed based on few measurements which show large variations. However, as we appointed concentrations that were on the high end for each land use, simulated concentrations are expected to be overestimated, which is not a disadvantage in this study, since risks to human health are estimated.

To validate the model, a comparison between simulated and measured concentrations of Cu and BaP is necessary. Although the measured data were not available for the simulated periods in 2015, pollutant monitoring in the Göta River was performed during a rain event (1-month rain) in September 2016. The measured data reveals that BaP concentrations were below the detection limit (0.05 µg/L) in all samples. The measured Cu concentrations varied between 3.0–7.4 and 2.9–12 µg/L at the north and south locations, respectively, which indicates elevated Cu concentrations compared to river background levels (median 1.2 µg/L, $n = 102$ over 22 months of monitoring, unpublished data). Although Cu concentration ≥ 10 µg/L was detected in only one grab sample, this sample can serve as a warning that 1-month rain events may give rise to pollutant concentrations in the Göta River exceeding the water quality standard (Livsmedelsverket 2015, Miljöförvaltningen Göteborg Stad 2013).

At the suggested bathing site Skeppsbron, which is the closest to the north monitoring site, the simulated BaP (< 0.05 µg/L) and Cu (approximately 1–6 µg/L) concentrations (Table 2) were in agreement with the measured BaP (< 0.05 µg/L) and Cu (3.0–7.4 µg/L) concentrations. River water was collected mainly after rainfall seized, suggesting that the peaks of stormwater and CSO discharges were missed. However, Figures 3 and 4 suggest that river water quality at certain sites is negatively affected hours to days after rainfall.

A comparison between simulated and measured concentrations in this case is only indicative since stormwater and CSO pollutant concentrations vary considerably between events (Lee et al. 2007, Madoux-Humery et al. 2015, McCarthy et al. 2007). Elevated pollutant concentrations in stormwater are generally correlated to factors such as antecedent dry period, which affects the accumulated load of pollutants on impervious surfaces, and rain intensity, as higher intensity leads to greater mobilisation capacity of solid pollutants, hence higher pollutant concentrations (Egodawatta et al. 2007, Vaze and Chiew 2002). These factors, however, are not considered in the model, as the appointed pollutant concentrations from different sources were assumed not vary over time.

Generally, concentrations of many organic pollutants are low in the water phase due to high hydrophobicity (log $K_{ow} > 3$), but e.g. polychlorinated biphenyls (PCB), PAHs and dioxins have been detected in the sediments of the Göta River. Also, metals including Cd, Cu, Pb, Hg and Zn were detected in the Göta River sediments (Johansson and Skrapste 2003). Consequently, the developed model may overestimate the concentrations of Cu and BaP in the water phase. However, settling of particles and particle-bound pollutants have not been accounted for in the model. The levels of Cu and BaP in the sediment phase must also be investigated, since human–sediment contact should be avoided, if pollutants levels are found alarming. In a refined model, the settling of particles could be included to indicate if, and in this case, where the particles settle and if they may become resuspended.

3.4 Mitigation measures to improve river water quality for recreational purposes

Load calculations (Table 1) and simulated concentrations of Cu and BaP (Table 2) suggest that stormwater has a more negative effect, compared to CSOs, on river water quality. Although the Rya WWTP gives rise to large Cu and BaP loads (Table 1), these discharges are not a threat to recreational water quality along the Göta River. From a chemical risk point of view, stormwater treatment is of utmost importance to improve receiving water quality in this case study. However, from a microbial risk point of view, mitigation of CSOs has been shown to be more important (Tyréns AB 2016). Therefore, if the goal is to achieve water quality that is safe for bathing, the city of Gothenburg needs to address both stormwater and CSO discharges.

The largest input of pollutants with stormwater is associated with traffic and roads (Figure 2, Supporting Information), often identified as major pollution sources to urban stormwater, followed by industrial land use (Markiewicz et al. 2017, Tang et al. 2013, Tiefenthaler et al. 2008). By implementing treatment of runoff from some of the major roads in Gothenburg, e.g. E6, E20, E45 and Lundbyleden with approximately 200 000 AADT (City of Gothenburg 2017), large water quality benefits would be gained. Underground retention or detention facilities have the potential to save valuable urban land while removing particles and bound pollutants as well as reducing peak flows (Drake et al. 2016, Tran and Kang 2013, US EPA 2001). Such a sedimentation facility already exists in Gårda in Gothenburg, where to runoff from 2.1 ha of the E6/E20 is drained and treated. The underground chambers were proven efficient for removing pollutants such as TSS, metals, PAHs, phthalates and alkylphenols, although tank design should be optimised to decrease bypass and increase treated water volumes (Björklund et al. 2009, Pettersson et al. 2005).

Replacing the combined sewer systems with separate sewers is crucial to achieve water quality goals in many urban areas. However, the renewal rate is very low due to high costs.

In this paper levels of Cu and BaP from stormwater and CSOs have been investigated, however, other diffuse discharges, e.g. oil leakage from ships and erosion from contaminated sites, could also contribute to pollution of the river; this needs to be taken into account when allowing bathing in the river (Johansson et al. 2003). The lack of recreational water quality guidelines is a pressing matter. WHO suggests that drinking-water guidelines may serve as a basis when defining recreational water quality guidelines (WHO 2003).

4 Conclusions

- The simulations indicate that water quality guideline values for Cu are exceeded at several sites, and that stormwater discharges generally give rise to higher Cu and BaP concentrations than CSOs. Although large pollutant loads are emitted from the wastewater treatment plant, these discharges do not affect water quality at the suggested bathing sites.
- Due to the location of point discharges and the river current inhibiting lateral mixing, the north shore of the river is better suited for bathing. Bathing at sites on the south shore, especially north of the downtown core, is discouraged because that area receives runoff from most major highways.
- Peak concentrations have short duration; however, increased concentrations of the pollutants may be present for several days after rainfall at selected bathing sites.
- If the goal is to achieve water quality that is safe for bathing, the city of Gothenburg needs to address both stormwater, which is the major source to chemical risks, and CSO discharges, which are the major sources to microbial risks. Mitigating stormwater from highways with high traffic counts, e.g. through underground sedimentation tanks, has the potential to considerably improve stormwater quality in general, as traffic is one of the largest contributors to deteriorated stormwater quality.
- The BaP results are deemed more uncertain than Cu due to lack of input concentration data based on few available measurements. The developed model may overestimate the concentrations of Cu and BaP in the water phase due to the exclusion of settling and particle-bound pollutants. In a refined model, the settling of particles could be included to indicate if, and in this case, where the particles settle and if resuspension is of importance.
- The lack of recreational water quality guidelines needs to be addressed.
- Hydrodynamic modelling is a useful tool for identifying suitable bathing sites in urban surface waters and areas of concern, where mitigation measures should be implemented to improve water quality.

Acknowledgements

The authors wish to acknowledge Olle Dahlberg, Sustainable Waste and Water (City of Gothenburg), for providing the Göta River water quality data; Hanna Sjöstedt, Parks and Landscape Administration (City of

Gothenburg), for collecting the water samples; and Sebastien Rauch, Chalmers University of Technology, for performing the metal analysis.

Funding

This work was funded by the respective institutions employing the authors.

References

Ahlman, S., Kant, H., Karlsson, P., Malm, A. and Svensson, G. (2004) Systemanalys Vasastaden Göteborg (Systems analysis of the urban area Vasastan, Gothenburg). Water, U. (ed), Göteborg, Sweden.

Ali, M. and Sreekrishnan, T.R. (2001) Aquatic toxicity from pulp and paper mill effluents: a review. Advances in Environmental Research 5(2), 175-196.

Björklund, K., Palm Cousins, A., Strömvall, A.-M. and Malmqvist, P.-A. (2009) Phthalates and nonylphenols in urban runoff: Occurrence, distribution and area emission factors. Science of the Total Environment 407(16), 4665-4672.

Brown, J.N. (2002) Partitioning of Chemical Contaminants in Urban Stormwater University of Otago, Dunedin, New Zealand

Camponelli, K.M., Lev, S.M., Snodgrass, J.W., Landa, E.R. and Casey, R.E. (2010) Chemical fractionation of Cu and Zn in stormwater, roadway dust and stormwater pond sediments. Environmental Pollution 158(6), 2143-2149.

CCME (1999) Canadian water quality guidelines for the protection of aquatic life: Polycyclic Aromatic Hydrocarbons (PAHs). Canadian Council of Ministers of the Environment (ed), Winnipeg, Canada.

CCME (2011) Canadian Environmental Quality Guidelines Summary Table: Water Quality Guidelines for the Protection of Aquatic Life. (CCME), C.C.o.M.o.t.E. (ed), Canadian Council of Ministers of the Environment (CCME).

City of Gothenburg (2017) Trafikmängder på olika gator (Traffic counts for different streets).

Dahlström, B. (2006) Regnintensitet i Sverige – en klimatologisk analys (Rain intensity in Sweden – a climatological analysis). Vatten, S. (ed), Stockholm, Sweden.

Davidsson, F. and Mattsson, A. (2013) Referensprovtagning i Gryaabs tunnlar 2012 - delrapport metaller (Reference sampling in the tunnels of Gryaab 2012 - subreport on metals). Gryaab (ed), Göteborg, Sweden.

De Brauwere, A., Ouattara, N.K. and Servais, P. (2014) Modeling fecal indicator bacteria concentrations in natural surface waters: A review. Critical Reviews in Environmental Science and Technology 44(21), 2380-2453.

Dienus, O., Sokolova, E., Nyström, F., Matussek, A., Löfgren, S., Blom, L., Pettersson, T.J.R. and Lindgren, P.-E. (2016) Norovirus Dynamics in Wastewater Discharges and in the Recipient Drinking Water Source: Long-Term Monitoring and Hydrodynamic Modeling. Environmental Science & Technology 50(20), 10851-10858.

Drake, J., Young, D. and McIntosh, N. (2016) Performance of an Underground Stormwater Detention Chamber and Comparison with Stormwater Management Ponds. Water 8(5), 211.

Dudka, S. and Adriano, D.C. (1997) Environmental Impacts of Metal Ore Mining and Processing: A Review. Journal of Environmental Quality 26(3), 590-602.

EEA (2016) Rivers and lakes in European cities: Past and future challenges. (EEA), E.E.A. (ed), European Environment Agency (EEA), Luxembourg.

Egodawatta, P., Thomas, E. and Goonetilleke, A. (2007) Mathematical interpretation of pollutant wash-off from urban road surfaces using simulated rainfall. Water Research 41(13), 3025-3031.

Eregno, F.E., Tryland, I., Tjomsland, T., Myrmel, M., Robertson, L. and Heistad, A. (2016) Quantitative microbial risk assessment combined with hydrodynamic modelling to estimate the public health risk associated with bathing after rainfall events. Science of the Total Environment 548-549, 270-279.

Eriksson, E. (2002) Potential and problems related to reuse of water in households. PhD Thesis, Technical University of Denmark, Kgs. Lyngby, Denmark.

European Commission (2000) Establishing a framework for the Community action in the field of water policy - Directive 2000/60/EC of the European Parliament and of the Council.

European Commission (2001) Establishing the list of priority substances in the field of water policy - Decision No 2455/2001/EC of the European Parliament and of the Council.

Gasperi, J., Sebastian, C., Ruban, V., Delamain, M., Percot, S., Wiest, L., Mirande, C., Caupos, E., Demare, D., Kessoo, M.D., Kessoo, Saad, M., Schwartz, J.J., Dubois, P., Fratta, C., Wolff, H., Moilleron, R., Chebbo, G., Cren, C., Millet, M., Barraud, S. and Gromaire, M.C. (2014) Micropollutants in urban stormwater: occurrence, concentrations, and atmospheric contributions for a wide range of contaminants in three French catchments. Environmental Science and Pollution Research 21(8), 5267-5281.

Göteborg Stad (2013) Bada mitt i stan: En förstudie av Jubileumsprojektet (Bathing in the city centre: A pre-studie of the Jubilee project). Älvstranden Utveckling AB (ed), Gothenburg, Sweden.

Health Canada (2012) Guidelines for Canadian Recreational Water Quality – Third Edition. Water, A.a.C.C.B., Healthy Environments and Consumer Safety Branch, (ed), Ottawa, Canada.

Henze, M., van Loosdrecht , M.C.M., Ekama, G.A. and Brdjanovic, D. (eds) (2008) Biological Wastewater Treatment: Principles, Modelling and Design, IWA Publishing, London, UK.

Herngren, L., Goonetilleke, A., Ayoko, G.A. and Mostert, M.M.M. (2010) Distribution of polycyclic aromatic hydrocarbons in urban stormwater in Queensland, Australia. Environmental Pollution 158(9), 2848-2856.

Hoyer, A.B., Schladow, S.G. and Rueda, F.J. (2015) A hydrodynamics-based approach to evaluating the risk of waterborne pathogens entering drinking water intakes in a large, stratified lake. Water Res. 83, 227-236.

International Agency for Research on Cancer (2012) Benzo[a]pyrene, pp. 111-144, Lyon, France.

Johansson, K. and Skrapste, A. (2003) Miljögifter i och kring Göta älv, ISSN 1403-168X PUBLIKATION 2003:57.

Johansson, K., Skrapste, A., Oscarsson, H., Olofsson, J., Olsson, P., H., O. and Wahlqvist, A. (2003) Miljögifter i och kring Göta älv.

Kayhanian, M., Suverkropp, C., Ruby, A. and Tsay, K. (2007) Characterization and prediction of highway runoff constituent event mean concentration. Journal of Environmental Management 85(2), 279-295.

Lee, H., Swamikannu, X., Radulescu, D., Kim, S.-j. and Stenstrom, M.K. (2007) Design of stormwater monitoring programs. Water Research 41(18), 4186-4196.

Lefebvre, O. and Moletta, R. (2006) Treatment of organic pollution in industrial saline wastewater: A literature review. Water Research 40(20), 3671-3682.

Liu, W.C., Chan, W.T. and Young, C.C. (2015) Modeling fecal coliform contamination in a tidal Danshuei River estuarine system. Sci. Total Environ. 502, 632-640.

Livsmedelsverket (2015) Livsmedelsverkets föreskrifter om dricksvatten (Livsmedelsverket's regulations on drinking water). National Food Agency Sweden (ed).

Luo, Y., Guo, W., Ngo, H.H., Nghiem, L.D., Hai, F.I., Zhang, J., Liang, S. and Wang, X.C. (2014) A review on the occurrence of micropollutants in the aquatic environment and their fate and removal during wastewater treatment. Science of the Total Environment 473–474, 619-641.

Madoux-Humery, A.-S., Dorner, S.M., Sauve, S., Aboulfadl, K., Galarneau, M., Servais, P. and Prevost, M. (2015) Temporal analysis of E. coli, TSS and wastewater micropollutant loads from combined

sewer overflows: implications for management. Environmental Science: Processes & Impacts 17(5), 965-974.
Makepeace, D.K., Smith, D.W. and Stanley, S.J. (1995) Urban stormwater quality: Summary of contaminant data. Critical Reviews in Environmental Science and Technology 25(2), 93-139.
Maniquiz-Redillas, M. and Kim, L.-H. (2014) Fractionation of heavy metals in runoff and discharge of a stormwater management system and its implications for treatment. Journal of Environmental Sciences 26(6), 1214-1222.
Markiewicz, A., Björklund, K., Eriksson, E., Kalmykova, Y., Strömvall, A.-M. and Siopi, A. (2017) Emissions of organic pollutants from traffic and roads: Priority pollutants selection and substance flow analysis. Science of the Total Environment 580, 1162–1174.
McCarthy, D.T., Mitchell, V.G., Deletic, A. and Diaper, C. (2007) *Escherichia coli* in urban stormwater: explaining their variability. Water Science and Technology 56(11), 27-34.
Miljöförvaltningen Göteborg Stad (2013) Miljöförvaltningens riktlinjer och riktvärden för utsläpp av förorenat vatten till recipient och dagvatten (Guidelines and benchmarks for discharges of polluted water to the receiving water and stormwater). Gothenburg, T.e.a.o.t.c.o. (ed), Gothenburg, Sweden.
Nielsen, K. (2015) Characterisation and Treatment of Nano-sized Particles, Colloids and Associated Polycyclic Aromatic Hydrocarbons in Stormwater. Ph.D. thesis, Technical University of Denmark, DTU Environment.
Nielsen, K., Kalmykova, Y., Strömvall, A.-M., Baun, A. and Eriksson, E. (2015) Particle phase distribution of polycyclic aromatic hydrocarbons in stormwater — Using humic acid and iron nano-sized colloids as test particles. Science of the Total Environment 532, 103-111.
Opher, T. and Friedler, E. (2010) Factors affecting highway runoff quality. Urban Water Journal 7(3), 155 - 172.
Pal, A., Jayamani, J. and Prasad, R. (2014) An urgent need to reassess the safe levels of copper in the drinking water: Lessons from studies on healthy animals harboring no genetic deficits. Neurotoxicology 44, 58-60.
Paxeus, N. and Friedrich Schroder, H. (1996) Screening for non-regulated organic compounds in municipal wastewater in Göteborg, sweden. Water Science and Technology 33(6), 9-15.
Pettersson, T.J.R., Strömvall, A.-M. and Ahlman, S. (2005) Underground sedimentation systems for treatment of highway runoff in dense city areas. Eriksson, E., Genc-Fuhrman, H., Vollertsen, J., Ledin, A., Hvitved-Jacobsen, T. and Mikkelsen, P.S. (eds), Copenhagen, Denmark.
Pokhrel, D. and Viraraghavan, T. (2004) Treatment of pulp and paper mill wastewater—a review. Science of the Total Environment 333(1–3), 37-58.
Prestes, E.C., Anjos, V.E.d., Sodré, F.F. and Grassi, M.T. (2006) Copper, lead and cadmium loads and behavior in urban stormwater runoff in Curitiba, Brazil. Journal of the Brazilian Chemical Society 17, 53-60.
Ravindra, K., Sokhi, R. and Van Grieken, R. (2008) Atmospheric polycyclic aromatic hydrocarbons: Source attribution, emission factors and regulation. Atmospheric Environment 42(13), 2895-2921.
Sansalone, J.J., Koran, J.M., Smithson, J.A. and Buchberger, S.G. (1998) Physical Characteristics of Urban Roadway Solids Transported during Rain Events. Journal of Environmental Engineering 124(5), 427-440.
Sörme, L. and Lagerkvist, R. (2002) Sources of heavy metals in urban wastewater in Stockholm. Science of the Total Environment 298(1-3), 131-145.
StormTac corporation (2016) StormTac database: Standard stormwater concentrations, v. 2016-08, 2016-08-29.

Tang, J.Y.M., Aryal, R., Deletic, A., Gernjak, W., Glenn, E., McCarthy, D. and Escher, B.I. (2013) Toxicity characterization of urban stormwater with bioanalytical tools. Water Research 47(15), 5594–5606.

Tiefenthaler, L.L., Stein, E.D. and Schiff, K.C. (2008) Watershed and land use–based sources of trace metals in urban storm water. Environmental Toxicology and Chemistry 27(2), 277-287.

Tran, D. and Kang, J.-H. (2013) Optimal design of a hydrodynamic separator for treating runoff from roadways. Journal of Environmental Management 116, 1-9.

Tyréns AB (2016) Badvattenkvalitet Göta älv – modelleringsstudie (Bathing water quality in the Göta River - modelling study). Kretslopp och vatten, G.S. (ed), Göteborg, Sweden.

University of Alabama (2015) National Stormwater Quality Database (NSQD), US EPA, International Stormwater BMP Database.

US EPA (2001) Storm Water Technology Fact Sheet On-Site Underground Retention/Detention. National Service Center for Environmental Publications (ed), United States Environmental Protection Agency, Office of Water, Washington, D.C.

US EPA (2012) Recreational Water Quality Criteria. Office of Water 820-F-12-058 (ed).

Vaze, J. and Chiew, F.H.S. (2002) Experimental study of pollutant accumulation on an urban road surface. Urban Water 4(4), 379-389.

WERF (2016) International Stormwater BMP Database v. 2016-11-17, Developed by Wright Water Engineers, Inc. and Geosyntec Consultants for the Water Environment Research Foundation (WERF), the American Society of Civil Engineers (ASCE)/Environmental and Water Resources Institute (EWRI), the American Public Works Association (APWA), the Federal Highway Administration (FHWA), and U.S. Environmental Protection Agency (EPA).

WHO (2003) Guidelines for safe recreational water environments. Volume 1: Coastal and Fresh Waters, Geneva, Switzerland.

Zgheib, S., Moilleron, R. and Chebbo, G. (2012) Priority pollutants in urban stormwater: Part 1 – Case of separate storm sewers. Water Research 46(20), 6683-6692.

Preprint version. Accepted paper: https://doi.org/10.1016/j.jenvman.2017.11.014

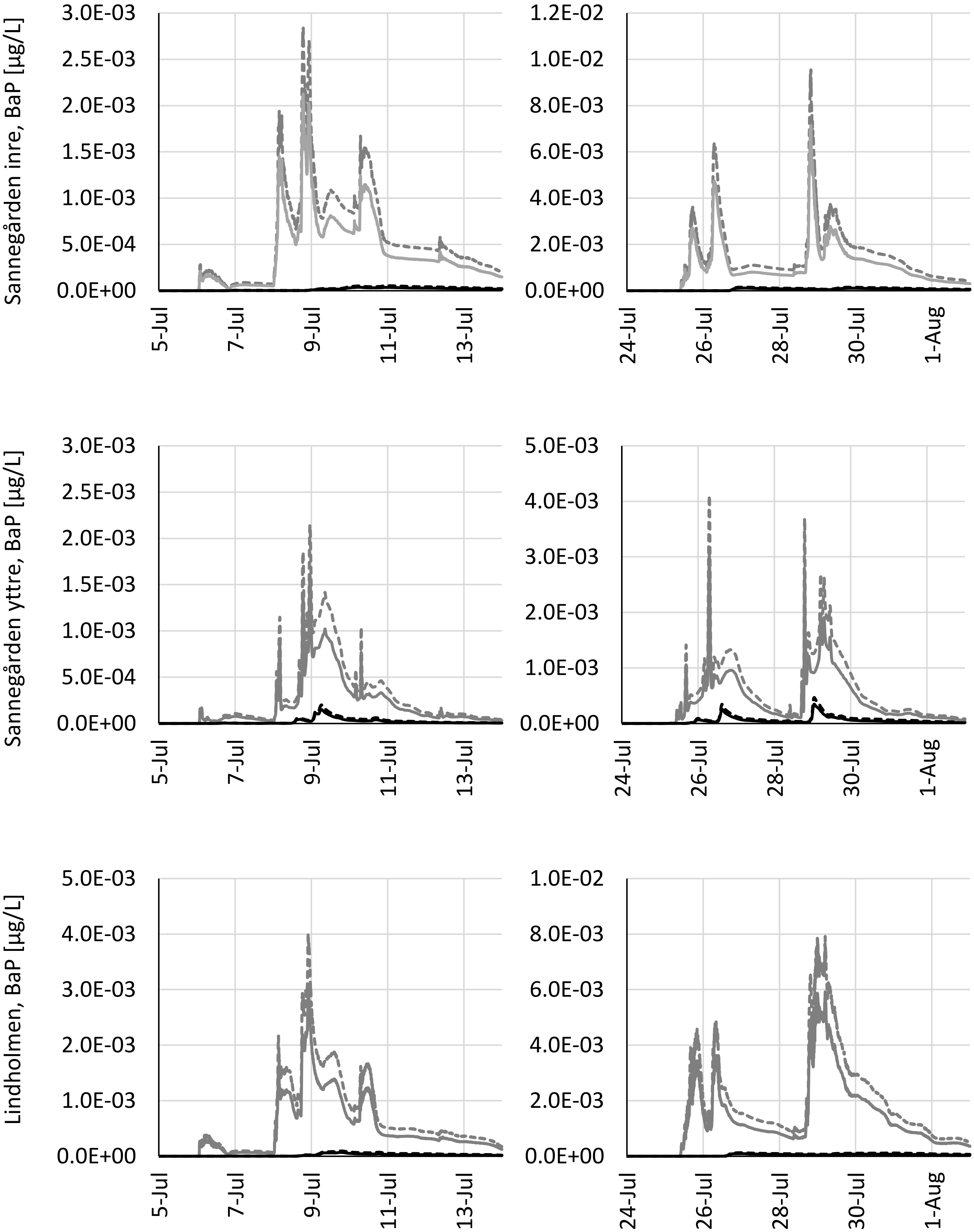
Supporting Information

Overview:

- Figure S1 – Map showing the locations and names of the discharge points into the Göta River.
- "sources_concentrations" – Excel file presenting the assumptions regarding the Cu and BaP concentrations in stormwater, CSO and wastewater discharges.
- Figure S2 – Time-series of the simulated BaP concentrations at three proposed bathing sites.

Preprint version. Accepted paper: https://doi.org/10.1016/j.jenvman.2017.11.014

Figure S1. *Map showing the modelled section of the Göta River with suggested bathing sites (green dots), discharge points of stormwater (red), CSOs (purple) and Rya WWTP (yellow).*


Sannegården inre, BaP [µg/L]
3.0E-03
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
5-Jul
7-Jul
9-Jul
11-Jul
13-Jul
1.2E-02
1.0E-02
8.0E-03
6.0E-03
4.0E-03
2.0E-03
0.0E+00
24-Jul
26-Jul
28-Jul
30-Jul
1-Aug
Sannegården yttre, BaP [µg/L]
3.0E-03
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00
5-Jul
7-Jul
9-Jul
11-Jul
13-Jul
5.0E-03
4.0E-03
3.0E-03
2.0E-03
1.0E-03
0.0E+00
24-Jul
26-Jul
28-Jul
30-Jul
1-Aug
Lindholmen, BaP [µg/L]
5.0E-03
4.0E-03
3.0E-03
2.0E-03
1.0E-03
0.0E+00
5-Jul
7-Jul
9-Jul
11-Jul
13-Jul
1.0E-02
8.0E-03
6.0E-03
4.0E-03
2.0E-03
0.0E+00
24-Jul
26-Jul
28-Jul
30-Jul
1-Aug

Preprint version. Accepted paper: https://doi.org/10.1016/j.jenvman.2017.11.014

Figure S2. *Simulated concentrations of BaP at the proposed bathing sites: Sannegården yttre, Sannegården inre and Lindholmen. Black and grey lines represent the influence of CSOs and stormwater, respectively. Solid and dotted lines represent the results based on the median and maximum concentrations (estimated based on reported values) at the sources, respectively.*