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Research article

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

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A B S T R A C T

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 health 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.

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

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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 health risks and recreational water quality by simulating the transport of metals and organic pollutants in the Göta River using a hydrodynamic model. In this case study, we simulated copper (Cu) and benzo[a]pyrene (BaP), as both compounds are frequently detected in stormwater and included in local, national and international water quality guidelines. 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

The Göta River is the largest river in Sweden, draining a 50,000 km^2 catchment area into the 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. The total annual precipitation in the city of Gothenburg amounts to approximately 855 mm (SMHI, 2017).

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 ($7 \leq n \leq 102$ between January 2014 and October 2015: $[As]_{max} = 0.42$; $[Benzo(a)pyrene]_{max} = <0.005$; $[Cd]_{max} = 0.02$; $[Cu]_{max} = 5.1$; $[Cr]_{max} = 0.90$; $[Hg]_{max} = <0.01$; $[Ni]_{max} = 1.1$; $[Pb]_{max} = 0.99$; $[Zn]_{max} = 7.0$, all concentrations in μg/L), which are all below the local water quality standards (Miljöförvaltningen Göteborg Stad, 2013). 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 human health risks from chemicals at the 13 proposed locations for bathing sites along the river (Fig. 1).

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 (Fig. 1). Within this stretch, the width of the river varies from approximately 100 m in the upstream parts to 400 m in the downstream parts, reaching more than 1000 m in the estuary (Fig. 1). The depth of the river reaches −15 m (SI1: Fig. S2). The water flow in the studied stretch of the river varied between 49 and 199 with a mean of 164 m^3/s during July–August 2015 (SI1: Fig. S3). All major freshwater tributaries that may influence the river flow and water quality within the model area were described in the model (SI1: Fig. S4).

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 the Rya WWTP, approximately 130–140 Mm^3 of 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