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Developing an easy-to-apply model for identifying relevant pathogen pathways into surface waters used for recreational purposes

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ABSTRACT

Swimming in inner-city surface waters is popular in the warm season, but can have negative consequences such as gastro-intestinal, ear and skin infections. The pathogens causing these infections commonly enter surface waters via several point source discharges such as the effluents from wastewater treatment plants and sewer overflows, as well as through diffuse non-point sources such as surface runoff.

Nonetheless, the recreational use of surface waters is attractive for residents. In order to save financial and organizational resources, local authorities need to estimate the most relevant pathways of pathogens into surface waters.

In particular, when detailed data on a local scale are missing, this is quite difficult to achieve. For this reason, we have developed an easy-to-apply model using the example of *Escherichia coli* and intestinal enterococci as a first approach to the local situation, where missing data can be replaced by data from literature. The model was developed based on a case study of a river arm monitored in western Germany and will be generalized for future applications.

Although the limits of the EU Bathing Water Directive are already fulfilled during dry weather days, we showed that the effluent of wastewater treatment plants and overland flow had the most relevant impact on the microbial surface water quality. On rainy weather days, combined sewer overflows are responsible for the highest microbial pollution loads.

The results obtained in this study can help decision makers to focus on reducing the relevant pathogen sources within a catchment area.

1. Introduction

Swimming in urban surface waters can lead to infections, especially gastroenteritis (Kistemann et al., 2012), but also e.g. cercarial dermatitis (Soldánová et al., 2013). The pathogens responsible for these illnesses enter surface waters at point sources, such as the effluent from wastewater treatment plants (WWTPs) and sewer overflows, as well as diffuse sources such as surface runoff from unpaved areas (overland flow). Depending on the sewer system and how impervious the surface is, combined sewer overflow (CSO) loads – in terms of bacteria and parasites – exceed the loads of WWTP effluents massively, especially after rainfall events (Medema and Schijven, 2001; Arnone and Walling, 2006; Rechenburg et al., 2006).

Additionally, several publications highlight agricultural land use as a major source for diffuse pollution of surface waters, particularly after specific events, such as the spreading of farm fertilizer. Permanent grassland is cultivated with grass or other herbaceous forage and may be an important source when it comes to the discharge of microorganisms (Franke et al., 2009; Kistemann et al., 2012; Schreiber and Kistemann, 2013; Schreiber et al., 2015). It is mostly fertilized with liquid manure and the application takes place from February to the late autumn, depending on the weather conditions (the ground has to be receptive and, thus, not frozen). The timespan of fertilization, therefore, correlates with the bathing season (May to September in central Europe). In addition to that, pasturing livestock may cause a direct discharge of pathogens into

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flowing water. In the state of North Rhine-Westphalia, where the Ruhr River is completely situated, 22,200 agricultural businesses spread 21,794,000 m^3 of liquid manure in 2010. The average usage of manure per agricultural business is 982 m^3. 47% of the liquid manure comes from cattle (DeStatis, 2011).

Indicator organisms enable public authorities to determine how polluted surface waters are and can be used as representative for numerous different organisms. *Escherichia coli* and intestinal enterococci (I. E.) are indicator organisms for fecal contaminations and used as such in the EU Bathing Water Directive (2006). A relevant statistical connection was found between the occurrence of these two organisms in bathing waters and gastrointestinal symptoms of swimmers (Wiedemann et al., 2006). Payment et al. (2003) and Medema et al. (2003) consider *E. coli* and enterococci as qualified to characterize raw water with regard to hygienic aspects. The EU Bathing Water Directive (2006) sets a limit of $900 \cdot (100\,\mathrm{ml})^{-1}$ *E. coli* (based upon a 90-percentile evaluation) and a limit of $330 \cdot (100\,\mathrm{ml})^{-1}$ I. E. (based upon a 90-percentile evaluation) as an auxiliary quantity for sufficient water quality.

There are several approaches to estimate the entry paths of bacteria into surface waters, especially from single sources (Frick et al., 2008; Kistemann et al., 2012; Ibekwe et al., 2013). However, most of these approaches require a lot of local data which are often not available or quite difficult to achieve. Helm et al. (2013) pointed out how mass balance-oriented models help to identify which emission sources play significant roles for the pollution of a surface water body and to develop integrated water quality management schemes. The authors used the model MONERIS which helps identifying nutrient pathways into a river and applied it on an area with limited access to local data.

A generalized model is missing so far for the entry pathways of pathogens. Existing models such as described in de Brauwere et al. (2014) focus on the water quality of the surface water in question, taking processes like sedimentation and degradation into consideration. However, very detailed data is necessary, including a flow model of the river which is not always available. In addition, the concentrations of pathogens released by diffuse pollution from agricultural areas have only been described very sparsely in literature, since measuring this particular stream is far from trivial (e.g. Kay et al., 2007; Kistemann et al., 2012).

Thus, we have developed an easy-to-apply model using the example of *E. coli* and I. E., as a first approach to the local situation, where missing data can be replaced by literature data. This is especially valuable for regions without sufficient financial abilities for detailed sampling campaigns. Other than MONERIS, this model is completely based on Monte Carlo simulations.

Our model should help decision makers focus on further investigating and reducing the relevant pathogen sources within a catchment area. Hence, we took into account the most relevant pathways into surface waters for the indicator pathogens, including those pathogen loads brought into an area under surveillance via the base flow of the river or its tributary streams.

The model was developed based on a case study of a river arm monitored in Western Germany and an average month during bathing season (May to September). In the research project "Sichere Ruhr" (Safe Ruhr), a part of the Ruhr River (Fig. 1) was investigated to determine concentrations of pathogens during a one-year period and to find possible ways to reduce them. The part of the river monitored includes some popular beaches, although swimming is officially banned.

The project region has been divided into several catchment areas of wastewater treatment plants. As can be seen in Fig. 2, the Ruhr River has several tributary waters. WWTPs and CSOs discharge into the tributary streams as well as into the main river. The average livestock unit (LU) per hectare within the catchment area of the Ruhr is 1.23 LU/ha (Lenzen, 2012).

2. Methods

2.1. Identifying relevant pathways

2.1.1. Concentration of pathogens related to precipitation events

On 23 days, samples were taken at a total of eight points in the Ruhr River. The sampling took place over a period of approximately one year, from April 2012 to May 2013, and encompassed rainy weather days as well as spells of dry weather. The two sampling points Fischereiverein and SeaSide Beach, situated at the Lake Baldeney (Fig. 1) were monitored fortnightly until December 2013. One additional sample was taken at the sampling point Löwental in September 2013.

Results from a literature review (e.g. Atherholt et al., 1998; Auerbach et al., 2009; Gasse, 2009) led to the assumption that precipitation would influence the concentrations in the Ruhr River. Thus, the results for the concentrations of *E. coli* and I. E. were evaluated by correlating precipitation amount on sampling days with the measured concentrations. Since these results will be used in the approach below, they are anticipated here: "dry weather days" were found to be days with rainfall less than 1 mm on the sampling day and on the two previous days, thus, there was a possibility of minimum runoff. "Rainy weather days" were sampling days with more than 1 mm of rainfall on the current day or on one of the rainfall two previous days.

For both groups, an evaluation according to the EU Bathing Water Directive (2006) was performed in order to find out whether a sufficient water quality was achieved based on all sampling days. This was done using an Excel sheet for calculating the 90- and 95-percentil values for *E. coli* and I. E. based on the specifications made in Annex II of the EU Bathing Water Directive, 2006.

2.1.2. Water flow

To evaluate the flow situation, we chose an offset for the water flow at the point of the level gauge "Hattingen". Further inflow into the survey area was provided by daily recorded effluent data from the WWTPs Essen-Burgaltendorf, -Sued, -Kupferdreh, -Kettwig and daily measured precipitation within the areas of the catchments as shown in Fig. 2. For the two tributary streams with sufficient data, inflow values were considered as well.

To evaluate the water quantity discharged by CSOs, we combined the effluent data from the WWTP with precipitation data: the each day's effluent of the WWTPs ($Q_{WWTP,dis}$) for the years 2010 to 2012 as well as the overall runoff coefficient (Ψ_M) for the catchment area and the catchment area relevant for runoff (a_r) was provided by the public water authority Ruhrverband, which is in charge of wastewater treatment in the project area. Due to measurement uncertainties, the flows were only calculated on monthly basis. Thus, the precipitation volume (Q_p) entering the sewer system could be quantified as:

$$Q_{p,m} = h_{p,m} \cdot \Psi_M \cdot a_r$$

where $Q_{p,m}$ is the monthly runoff entering the sewer system; $h_{p,m}$ is the monthly precipitation as mean value from precipitation heights measured at relevant points in the catchment area; Ψ_M is the mean overall runoff coefficient; a_r is the catchment area relevant for runoff.

In case of "dry weather days" (precipitation sum less than 1 mm on the same day and less than 1 mm on the preceding two days), the dry weather discharge of each WWTP (Q_{dry}) was equivalent to the measured inflow. On "rainy weather days" (all other days), the amount of wastewater without rainwater treated by the WWTP (Q_{rain}) was set as a mean value of the monthly dry weather discharge. In case of a month with no dry weather days, it was set