Monte Carlo simulation for localisation and volume estimation of wastewater contamination in stormwater sewers

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ABSTRACT

In separate sewerage systems the sewage may find its way into the stormwater sewer network, impairing the quality and increasing the risks to public health and aquatic organisms. Detecting the presence and localising the point of ingress of wastewater in stormwater systems can be a challenging task because of the variable sources, regularity, consistency and flow rates of incoming wastewater. This paper suggests a method for the estimation of the volumes of wastewater inflow to a stormwater system and localising its point of ingress by using Monte Carlo simulation. The developed method showed varying efficiency depending on the selected combination of pollutant parameters. More experiments on the rates of concentration changes of parameters over the travel distance are suggested to increase the accuracy of the method.

KEYWORDS

Wastewater contamination, stormwater, Monte Carlo simulation, illicit connections
1 INTRODUCTION

In separate sewer systems wastewater that finds its way into the stormwater sewer network is not that rare (Schmidt and Spencer, 1986; Pitt, 2004). Any illicit inflows of wastewater may be transferred through the stormwater sewers and, where such systems do not include any stormwater treatment facilities, ultimately outfall into receiving waters, impairing their quality and increasing the risks to public health and aquatic organisms (Ouattara et al., 2014).

Detecting the presence and localising the point of ingress of wastewater in stormwater systems can be a challenging task because of the variable sources, regularity, consistency and flow rates of incoming wastewater (Panasiuk et al., 2015). The concentrations of the indicator parameters may change along the stormwater sewer length due to dilution, dispersion, chemical, physical, and microbiological processes (Rieckermann et al., 2005; Tyagi et al., 2009). The study performed by Panasiuk et al. (2016) showed a decrease in the concentration of all the analysed parameters over a 340 m long study section, except for turbidity.

This paper suggests a method for the estimation of the volumes and location of the point of wastewater ingress to a stormwater system based on the concentration decrease rate of indicator parameters (Panasiuk et al., 2016). Location and volume are determined by using Monte Carlo simulation to generate the probability distribution of the possible distances away from the wastewater point of ingress and the observed fractions of wastewater in the stormwater sewer.

2 MATERIAL AND METHODS

2.1 Experimental setup

A field study was performed to evaluate the travel distance of the contamination along a stormwater sewer as a factor affecting the rate of concentration decrease of six indicator parameters (E. coli, total coliform, Enterococci, conductivity, TSS, and ammonium). A 340 m long part of a separate sewer system with no tributary inflows and negligible infiltration along the study section was selected in Östra Kronan (Luleå, Sweden) for the field study (Figure 1, left). The experiments simulated a constant inflow of wastewater into the stormwater sewer (Figure 1, centre, right) by pumping wastewater from wastewater sewer (1) using a pump (2) through the hose (3) to a holding tank (4) equipped with the stirrer (5). A peristaltic pump (6) dosed wastewater with a given flow rate through a hose (7) to the invert of the stormwater sewer (8) during the experimental runs. For this study, sampling stations SW2, SW3 and SW4 were installed along the study section, 70 m, 210 m and 340 m respectively downstream from the start of the study section (see Figure 1, left). Samples were also taken from the wastewater tank from which the inputs were pumped. A detailed description of the experimental setup, instrumentation, sampling and analytical methods is given by Panasiuk et al. (2016).

Figure 1. Left: diagrammatic plan of the sampling site located in the town Luleå, north of Sweden. On the scheme below the map, the sampling sites BF, SW1, SW2, SW3 and SW4 are marked together with the distance from the start of the study section, as well as the inclination of each pipe length between manholes. Centre: a sketch of the pumping facilities installed at the upstream end of the study section. For number descriptions, see the text above. Right: Photo of the wastewater holding tank with installed stirrer and peristaltic pump
2.2 Monte Carlo simulation

The estimation of wastewater ingress volumes to the stormwater system and localising its point of ingress was carried out Monte Carlo simulation based on two equations (solutions of the system of two simultaneous equations (1) which describes linear changes in concentrations over the distance for two parameters analysed) (Panasiuk et al., 2016):

\[
\begin{align*}
C_1 &= a_1x + WW_1 \cdot F \\
C_2 &= a_2x + WW_2 \cdot F \\
\Rightarrow x &= \frac{C_1WW_2 - C_2WW_1}{a_1WW_2 - a_2WW_1} \\
F &= \frac{C_2WW_2 - C_1WW_1}{a_2WW_1 - a_1WW_2}
\end{align*}
\]

where \(x\) is the distance from the point of wastewater ingress; \(F\) is the fraction of the wastewater inflow in the resulting total flow in the stormwater sewer; \(C_i\) is the concentration of the parameter \(i=\{1,2\}\) in the sample taken from the stormwater sewer; \(a_i\) is the rate of the concentration decrease for the parameter \(i=\{1,2\}\); and \(WW_i\) is the concentration of the parameter \(i=\{1,2\}\) in the wastewater.

Using only equations (2) and (3) for well-defined rates of concentration decrease \(a_1\) and \(a_2\), a single value for each of the distance and the fraction of wastewater may be obtained. Monte Carlo simulations of both the distance away from the point of wastewater ingress and the wastewater fraction were undertaken in order to increase the robustness of the method.

The results from the field experiments described in Panasiuk et al. (2016) were used as an input to the Monte Carlo simulation: concentration of parameters analysed in the wastewater tank and along the study sewer length (at stations SW2, SW3, SW4) as well as the rates of concentration decrease \((a_i)\) of the parameters. A simplified procedure assuming a uniform probability distribution for the simulation of 2000 values of decrease rates for each parameter analysed was undertaken. In total, the simulation generated 2.16 billion values for the 540 probability distributions of both the wastewater fractions and the distance away from the point of wastewater ingress.

3 RESULTS

Generated values for the possible fractions of wastewater were distributed with the step of 0.5% (with the range of 0–100%) and the possible distances away from the wastewater point of ingress — with the step of 10 m (with the range of 0–1000 m). The most probable fraction and distance (with the maximum number of occurrences) were defined and compared with the known wastewater fraction (as percent errors) and distance away from the upstream end of the study section (as absolute errors).

Based on 540 calculated values of the percent errors for both the wastewater fractions (Figure 2, left) and the absolute errors for the distance (Figure 2, right), two cumulative distribution functions (CDF) were constructed and 10\(^{th}\), 25\(^{th}\), 50\(^{th}\), 75\(^{th}\) and 90\(^{th}\) percentiles found.

Figure 3 shows 540 obtained results of the simulation for the wastewater fractions (in form of percent errors) (Figure 3, top-left) and the distances (in form of absolute errors) (Figure 3, bottom-right). The colour-coding in Figure 3 is based on the percentiles from the CDF analysis (Figure 2).

![Figure 2. Cumulative distribution functions of simulated values. Left: percent errors for simulated wastewater fractions. Right: the absolute errors for simulated distances away from the wastewater point of ingress. Dashed lines show 10\(^{th}\), 25\(^{th}\), 50\(^{th}\), 75\(^{th}\) and 90\(^{th}\) percentiles. Colour coding above the scale is used in Figure 2.](image-url)
Figure 3. Top-left: the percent errors ($\delta F$) of the most probable wastewater fraction as compared with the known wastewater fraction in the stormwater sewer. Bottom-right: The absolute errors $\Delta x$ (presented in tens of meters for space economy) of the simulated distances away from the point of wastewater ingress from the known distances between the sampling stations and the upstream end of the study section.

4 DISCUSSION

Further analysis of the results of the Monte Carlo simulation for the estimation of the wastewater fraction (Figure 3, top-left) and the distance (Figure 3, bottom-right) showed varying accuracy for the fifteen parameter combinations in finding the most probable values of fraction and distance as compared with the known values. Performance results are presented in Figure 4.

Figure 4. Performance of fifteen parameter combinations in finding most probable fraction of wastewater in the stormwater sewer (left) and most probable distance away from the wastewater point of ingress (right): Enterococci (ENT), total coliforms (TCF), E. coli (ECO), TSS, ammonium (NH4), and conductivity (Cond). Red asterisks show simulations resulted in an empty probability distribution ($\gamma_{zim} = 0$), black asterisks show outliers.

The accuracy of the estimation of both the wastewater fraction and the distance away from the
contamination point of ingress by the suggested Monte Carlo simulation (under the conditions described in Panasiuk et al. (2016)) depended mostly on the selected combination of the parameters (see Figure 4). No significant influence on the efficiency of the suggested method for the wastewater fraction estimation was shown from the initial concentration of the contamination, as indicated by the results of a Tukey multiple test. The efficiency of the distance estimation was affected by the initial concentration of wastewater (20%, 45% and 100% of baseflow present in the stormwater sewer for the Runs 1, 2 and 3, respectively): Run 1 had higher precision in comparison with Run 3 and this difference was statistically significant, while Run 2 was not statistically different from either Run 1 or Run 3 (data not presented). Finally, the precision of the Monte Carlo simulation for the estimation of both the fraction and the distances away from the wastewater point of ingress in the presented paper was not statistically different within the tested range of distances.

5 CONCLUSIONS

A method for the estimation of wastewater ingress volumes to a stormwater system and localising its point of ingress by using Monte Carlo simulation was developed. The accuracy of the estimation of both the wastewater fraction and distance away from the contamination point of ingress varied to a great extent depending on the selected combination of parameters (Figure 4): for example, for conductivity and TSS the percent error between the most probable and actual wastewater fractions in the sewer could be less than 2%, while TSS combined with microbiological parameters failed as a combination to estimate the wastewater fraction in the sewer. For the distance estimation, the combination of using concentrations of ammonium and E. coli showed the best results (with several cases of exactly same simulated and known distances). More experiments on the rates of concentration changes of parameters over the travel distance are suggested to increase the accuracy of the method.

LIST OF REFERENCES


