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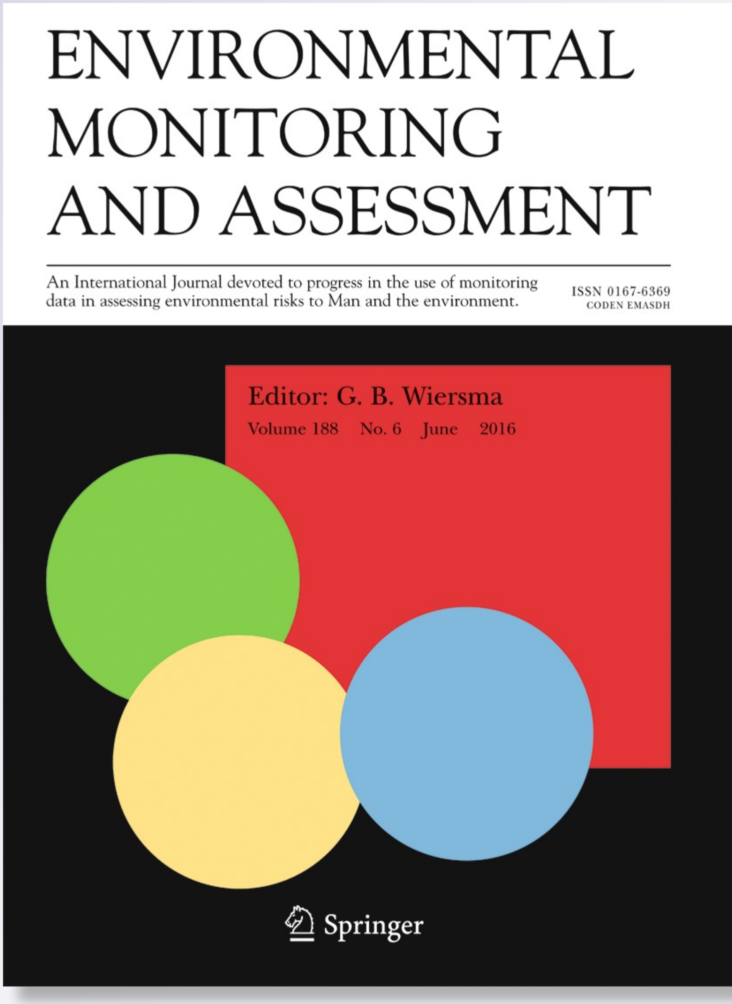

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Influence of sampling intake position on suspended solid measurements in sewers: two probability/time-series-based approaches

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Abstract Total suspended solid (*TSS*) measurements in urban drainage systems are required for several reasons. Aiming to assess uncertainties in the mean *TSS* concentration due to the influence of sampling intake vertical position and vertical concentration gradients in a sewer pipe, two methods are proposed: a simplified method based on a theoretical vertical concentration profile (SM) and a time series grouping method (TSM). SM is based on flow rate and water depth time series. TSM requires additional *TSS* time series as input data. All time series are from the Chassieu urban catchment in Lyon, France (time series from 2007 with 2-min time step, 89 rainfall events). The probability of measuring a *TSS* value lower than the mean *TSS* along the vertical cross section (*TSS* underestimation) is about 0.88 with SM and about 0.64 with TSM. TSM shows more realistic *TSS* underestimation values (about 39 %) than SM (about 269 %). Interquartile ranges (IQR) over the probability values indicate that SM is more uncertain (IQR = 0.08) than TSM (IQR = 0.02). Differences between the two methods are mainly due to simplifications in SM (absence of *TSS* measurements). SM assumes a significant asymmetry of the *TSS* concentration profile along the vertical axis in the cross section. This is compatible with the distribution of *TSS* measurements found in the TSM approach. The methods provide insights towards an indicator of the measurement performance and representativeness for a *TSS* sampling protocol.

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Keywords Concentration profile · Metrology · Particulate pollutants · Propagation of uncertainties · Representativeness

Introduction

Total suspended solid (*TSS*) measurements in urban drainage systems are often required for scientific, legal, environmental, and operational reasons, as particulate matter constitutes a major source of surface water contamination (Ashley et al. 2004; Chebbo and Gromaire 2004). However, the reliability of *TSS* measurements strongly depends on the quality of the collected samples, which should be a representative of real field conditions in the monitored sewer pipe (Larrarte 2008; Métadier and Bertrand-Krajewski 2012). Therefore, appropriate data acquisition and validation methodologies for *TSS* measurements in urban drainage systems are required (Bertrand-Krajewski and Muste 2007). Aiming to estimate data quality, intensive investigations have been carried out towards the assessment of uncertainties in online and laboratory *TSS* measurements (e.g., Joannis et al. 2008; Métadier and Bertrand-Krajewski 2011). However, the influence of field sampling conditions (e.g., sampling intake position, sampling flow velocities, or sampling pipe orientation) on the representativeness of *TSS* measured values has not been equivalently addressed recently in the literature according to authors' knowledge (Shelley 1977; Berg 1982; Rossi 1998; Larrarte and Pons 2011).

Indeed, one specific uncertainty source in *TSS* measurements lies in the sampling intake position through the sewer cross section (Shelley 1977; Rossi 1998; Kafi-Benyahia et al. 2006; Larrarte 2008; Larrarte and Pons 2011), which is frequently neglected by implicitly assuming that point-measured values are equal to the cross section mean concentration. This hypothesis seems to be valid in sewers with high enough flow velocities (Kafi-Benyahia et al. 2006; Larrarte 2015), where fully mixed flow conditions can be guaranteed (Raudkivi 1998). However, *TSS* vertical gradients might be non-negligible under other hydrodynamic conditions corresponding to lower velocities (Verbanck 1993, 1995; Ashley and Crabtree 1992; Ashley et al. 1994; Ristenpart 1995; Ristenpart et al. 1995; Ahyerre 1999). In this case, the difference between point measured and cross section mean concentrations can be therefore attributed to (i) variation of the position of the cross section mean concentration linked to vertical and horizontal concentration profiles due to hydrodynamics, (ii) variations of the sampling intake position through the cross section due, e.g., to oscillations of the sampling tube or to other experimental constraints (Larrarte and Pons 2011), and (iii) uncertainties in physical variables (e.g., flow rate measured at each time step, roughness coefficient, geometric properties).

In this paper, two methods are presented and applied comparatively to a case study in order to evaluate how the position of the sampling intake tube, the vertical concentration profile, and other uncertainty sources may lead to over- or underestimation of the cross section mean *TSS* concentration. More specifically, the methods allow estimating the probability that sampling *TSS* concentrations at a random point of the sewer vertical cross section (for given a flow rate) lead to over- or underestimation of the true vertical mean *TSS* concentration. This information can then be used to correct possible errors in measured *TSS* data.

Materials and methods

Data set

The simplified method (SM) is applied with flow rate Q (m^3/s) data determined from water depth H (m) and mean flow velocity U_m (m/s) measurements. The time series method (TSM) in addition includes *TSS* concentrations (mg/L) estimated from online turbidity measurements. The experimental time series were measured with a 2-min time step for 89 rainfall events in 2007 in Chassieu, France. The Chassieu 185-ha industrial catchment is equipped with a separate stormwater sewer system (more details about the catchment are given in, e.g., Métadier and Bertrand-Krajewski 2012). For SM, information and data include (i) the time series of the wet cross section A (m^2) derived from the H time series, (ii) the time series of the wet perimeter P (m) derived from the H time series, (iii) the sewer pipe slope S (m/m), and (iv) the settling velocity w_s (m/s) of suspended solids (details about settling velocity measurements are given in Torres and Bertrand-Krajewski 2008 and Chebbo and Gromaire 2009). Standard uncertainties in all above data are also needed for calculations. Input data and their uncertainties are given in Table 1.

Simplified method (SM)

The field conditions in which the samples are taken in the sewer pipe and the *TSS* concentration profile are illustrated in Figs. 1 and 2, where z (m) is the sampling intake depth, H (m) is the total water depth, and $y_{\bar{c}}$ (m) is the depth corresponding to the vertical mean concentration.

Previous studies (Coleman 1982; Verbanck 2000) propose to represent the vertical concentration profile in a pipe with the following equation:

$$\frac{C_h}{C_{a^*}} = \left(\frac{h}{a^*}\right)^{-\eta} \quad (1)$$

where $\eta = \frac{w_s}{\kappa U^*}$ (-) is the Rouse number, C_h (mg/L) is the concentration at depth h (m) above the invert, C_{a^*} (mg/L) is the concentration at the reference depth a^* (m) above the invert, U^* (m/s) is the shear velocity, and $\kappa = 0.4$ (-) is the Von Karman constant. The shear velocity is computed as follows (Verbanck 1995):

$$U^* = \sqrt{\frac{gAS}{P}} \quad (2)$$

where A (m^2) is the wet cross section, P (m) is the wet perimeter, S is the pipe slope (m/m), and g is the gravity (m/s^2). Thus, the Rouse number η can be written:

$$\eta = \frac{w_s}{\kappa}\sqrt{\frac{P}{gAS}} \quad (3)$$

Table 1 Input data and their uncertainties

Input variable	Input value	Source	Standard uncertainty/pdf	Source
Diameter D	$\overline{D}=1.6$ m	Métadier (2011)	$u(D)=0.002$ m	Muste et al. (2012)
Settling velocity w_s	$\overline{w_s}=2.8\text{e-}4$ m/s	Torres (2008)	$u(w_s)=0.13\ \overline{w_s}$ normally distributed	Torres (2008)
Pipe slope S	$\overline{S}=0.01$ m/m	Métadier (2011)	$u(S)=0$ m/m	Métadier (2011)
Water depth H	$\overline{H}=$ H m	Métadier (2011)	$u(H)=0.0075$ m normally distributed	Métadier (2011)
TSS	$\overline{TSS}=TSS$ mg/L	Métadier (2011)	Variable over the time series	Métadier (2011)

Hence, both the shape of the vertical concentration profile and the depth $y_{\bar{c}}$ of the mean concentration depend on the flow rate Q. For high enough values of Q (turbulent fully mixed condition), the vertical concentration profile might be expected to show a more uniform distribution along the vertical axis (as the Rouse number exponent η in Eq. 1 gets lower than about 0.6) (see details in Raudkivi 1998). In contrast, for low Q values, the TSS concentration will be higher near the pipe invert compared to the free surface. Although Eq. 1 remains widely used in the context of urban drainage, one should bear in mind that alternative forms of this equation are obtained when considering additional hypotheses about velocity profile, flow stratification, and hydrodynamic interactions (e.g., Verbanck 2000; Cantero-Chinchilla et al. 2016).

The problem therefore resides in estimating how much the measured TSS value at depth z deviates from the mean TSS concentration ($\overline{TSS}$) located at depth $y_{\bar{c}}$, with the above theoretical assumptions. The proposed method is illustrated in Fig. 3. $y_{\bar{c}}$ is considered as a random variable with a cumulative distribution function (CDF) based on the shape of the vertical concentration profile proposed by Coleman (1982) and Verbanck

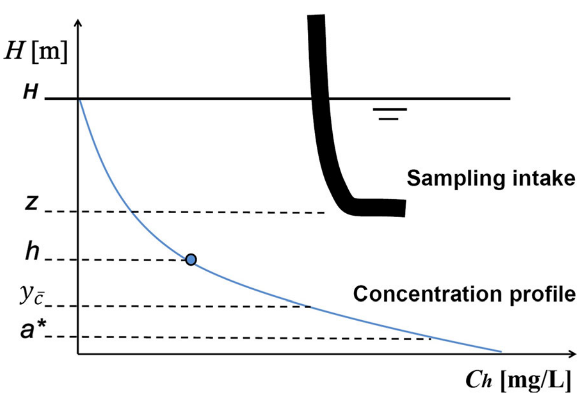

Fig. 1 Scheme of the concentration profile and the sampling tube

(2000) (Eq. 1), as there is usually a lack of data for calculating C_{a^*} and a^*. In addition, their estimation by semi-empirical equations developed for specific site conditions and circumstances can lead to erroneous results, as these values have shown to be case-dependent (e.g., Ristenpart 1995). The CDF curve is thus calculated by normalizing Eq. 1, making it independent from C_{a^*} and a^* and consistent with a CDF such that $P(z=0>y_{\bar{c}})=0$ and $P(z=H>y_{\bar{c}})=1$ (Fig. 3f). In general terms, $P(z>y_{\bar{c}})=0.5$ when z is equal to the median of $y_{\bar{c}}$, to be called $med[y_{\bar{c}}]$. The probability $P(z>y_{\bar{c}})$ that a random sampling depth z is higher than the point where $\overline{TSS}$ is located should be equal to $P(TSS<\overline{TSS})$, i.e., the probability of underestimating $\overline{TSS}$. The probability of non-exceedance of $\overline{TSS}$ can be thus computed by evaluating any sampling point z (where $0\leq z\leq H$) over the CDF of $y_{\bar{c}}$ (Fig. 3g). Cases for which z is lower than $med[y_{\bar{c}}]$ will result in a high probability of overestimating $\overline{TSS}$.

The Rouse number η plays a role in the shape of the CDF, leading to expect a dynamic behavior of $P(TSS<\overline{TSS})$ for different Q values. Regarding situations in which $med[y_{\bar{c}}]$ is close to the pipe invert, i.e., low Q values and curved vertical concentration profiles, a sampling point z close to H (i.e., near the free surface) might lead to a high probability of underestimating $\overline{TSS}$. For high enough values of Q with fully mixed condition, $P(TSS<\overline{TSS})$ or $P(z>y_{\bar{c}})$ can be expected to be close to 0.5, for all $0\leq z\leq H$. In theory, the optimum scenario is obtained if the sampling point z is equal to $med[y_{\bar{c}}]$.

With the Monte Carlo (MC) method, two sources of variability in $P(TSS<\overline{TSS})$ are accounted for (i) normal distributions to account for measurement uncertainties in physical variables: Q and h both at each time step, w_s and D (Fig. 3a, b), and (ii) uniformly distributed sampling depth z along the vertical axis (Fig. 3d). With this method, 1000 MC simulations have been done respectively for these two sources,