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### ► To cite this version:

Xiaoxiao Zhu, Vincent Chatain, Mathieu Gautier, Denise Blanc-Biscarat, Cécile Delolme, et al.. Combination of Lagrangian Discrete Phase Model and sediment physico-chemical characteristics for the prediction of the distribution of trace metal contamination in a stormwater detention basin. *Science of the Total Environment*, 2020, 698, pp.134263. 10.1016/j.scitotenv.2019.134263 . hal-02292220

**HAL Id: hal-02292220**

**<https://hal.science/hal-02292220>**

Submitted on 21 Dec 2021

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1 **Combination of Lagrangian Discrete Phase Model and sediment physico-chemical**  
2 **characteristics for the prediction of the distribution of trace metal contamination in a**  
3 **stormwater detention basin**

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8 **Abstract**

9 Elevated trace metal concentrations in sediments poses a major problem for the management of  
10 stormwater detention basins. These basins provide a nature-based solution to remove particulate  
11 pollutants through settling, but the resuspension of these contaminated deposits may impact the  
12 quality of both surface and groundwater. A better understanding of trace metal distribution will help to  
13 improve basin design and sediment management. This study aims to predict the distribution of trace  
14 metal contamination in a stormwater detention basin through (i) investigation of the correlation  
15 between metal content in sediments and their settling velocity, and (ii) the coupling of such  
16 correlation with a Lagrangian Discrete Phase Model (LDPM). The correlation between Fe, Cr, Cu, Ni,  
17 Pb contents and the settling velocity is firstly investigated, based on the sediments collected from 6  
18 sites (inlet and 5 traps at the bottom of a detention basin situated in Chassieu, France) during 5  
19 campaigns in 2017. Results show that Fe is strongly correlated to settling velocity and can be  
20 considered as a good indicator of trace metal contents. The derived correlation is then combined with  
21 a LDPM for the prediction of trace metal distribution, producing results consistent with *in situ*

22 measurements. The proposed methodology can be applied for other stormwater basins (dry or wet). As  
23 described in this article, the interactions between hydrodynamics and sediment physico-chemical  
24 characteristics is crucial for the design and management of stormwater detention basins, allowing  
25 managers to target the highest contaminated sediments.

26 **Key words:** Hydrodynamics, Metal contamination, Sediment, Settling velocity, Stormwater treatment

## 27 **1. Introduction**

28 Stormwater detention basins, among the many stormwater control measures (SCMs), are used to  
29 intercept and trap sediments by sedimentation (e.g. Marsalek and Marsalek 1997; Maniquiz-Redillas  
30 et al., 2014). They are widely used in most developed countries, such as France, Canada, US and other  
31 European countries (Urbonas, 1994). Since most of the pollutants, such as trace metals, polycyclic  
32 aromatic hydrocarbons (PAHs) and some pathogenic bacteria, are transported in a predominantly  
33 particulate form in urban stormwater (e.g. Barbosa et al., 2012; Gasperi et al., 2014; Zgheib et al.,  
34 2012), stormwater detention basins play an important role in the decontamination of stormwater by  
35 means of settling processes. A better understanding of key mechanisms in these basins is important to  
36 improve hydraulic and pollutant removal performance. Sediment movement in detention basins or  
37 reservoirs depend on their characteristics, e.g. size, shape, cohesive aspect, density, and settling  
38 velocity (Loch, 2011). It also depends on the residence time, which in return is controlled by the  
39 basin's geometry and flow patterns (Verstraeten and Poesen, 2000; Zhang, 2009; Akan, 2010). While  
40 the interactions between hydrodynamics and physico-chemical characteristics are of importance, they  
41 have not commonly been considered during the basin design phase, which to date has been primarily  
42 focused on hydraulic performance (e.g. Persson, 2000). In addition, the accumulated contaminated

43 deposits can be resuspended by incoming stormwater, subsequently being transported to the  
44 downstream aquatic environment. Sediment aerosolization could also pose a microbiological risk for  
45 humans through inhalation of aerosols during maintenance (Bernardin-Souibgui et al., 2018). Hence,  
46 appropriate management of accumulated contaminated sediments is crucial. Sustainable management  
47 of contaminated sediments is challenging, due to (i) expensive transportation, treatment and recycling  
48 fees, and (ii) limited reliable and suitable treatment and recycling options (e.g. Petavy et al., 2009). It  
49 is therefore essential to determine the distribution of contamination in stormwater detention basins  
50 and target the priority zones for treatment and intervention.

51 A thorough geochemical characterization of settled sediments can be used to determine the  
52 contamination distribution in stormwater detention basins. (Jang et al., 2010; Tedoldi et al., 2017).  
53 However, a large number of samples are needed, and their collection and characterization are  
54 expensive and time-consuming. Numerical models, on the other hand, are an effective and low-cost  
55 approach to predict the distribution of contamination. A chemical model was proposed by Vezaro et  
56 al. (2010) to simulate the removal of micropollutants in such basins based on relevant removal  
57 processes, such as settling, volatilization, sorption, biodegradation and abiotic degradation. This  
58 model, however, fails under complex hydrodynamic conditions in basins (Sebastian et al., 2014c) as  
59 the interactions between hydrodynamics and physico-chemical characteristics are ignored. The  
60 combination of Lagrangian Discrete Phase Model (LDPM) and the correlation between physical and  
61 chemical characteristics can be an appropriate alternative. Indeed, the simulation of particle transport  
62 provides a quick, convenient and low-cost way to characterise particle movement and predict  
63 preferential deposition zones of the particles and their associated pollutants. Such an approach permits  
64 alternative basin geometries to be compared, facilitating the design process. For example, a LDPM

65 implemented in computational fluid dynamics (CFD) package allows particle transport mechanisms in  
66 stormwater detention basins to be simulated, with particle physical characteristics used as model  
67 inputs (Adamsson et al., 2003; Yan et al., 2014). Finally, the transport mechanisms of pollutants can  
68 be simulated by implementing the correlation between particle physical and chemical characteristics  
69 using outputs of LDPM simulations or other solid transport model results.

70 Trace metals are considered as priority stormwater chemical pollutants related to urban activities. The  
71 decision No. 2455/2001/EC issued by the European Parliament and Council listed 33 priority  
72 substances, including Ni, Pb and their compounds. Zgheib et al. (2008) extended the list to 88  
73 individual substances, including Cr and Cu. Iron, as a major earth element, plays a key role in the  
74 geochemistry of soils and sediments and is of great importance to many metals cycling processes  
75 (Taylor and Kauhauser, 2011). Iron oxides are also important for the sorption of trace metals (Bradl,  
76 2004; Whitaker and Duckworth, 2018). As far as physical characteristics are concerned, settling  
77 velocity is an integrated property of particulate pollutants, as it is related to multiple characteristics  
78 such as diameter, density, shape and surface roughness (Loch, 2001). Several investigations are  
79 reported in the literature regarding both trace metal contents (Becouze-Lareure et al., 2019; Sébastien  
80 et al., 2014a) and particles' settling velocities in stormwater detention basins (Torres et al., 2007; Yan  
81 et al., 2014). However, to the best of our knowledge, little is known concerning the relationship  
82 between metal contents, particularly Fe, and settling velocity in urban stormwater detention  
83 components. Bentzen and Larsen (2009) investigated such relationship in a wet detention pond of  
84 road runoff, where high Cd, Cr, Zn and Ni contents were found associated with low settling velocities  
85 while the tendency for Cu and Pb was unclear. However, the conclusions were empirically drawn  
86 without quantitative analyses. Torres et al. (2007) found a significant correlation among median

87 settling velocity ( $V_{50}$ ) and contents of Cd, Cu, Pb and Zn in a stormwater detention basin, but metal  
88 contents with respect to different fractions of settling velocities were not considered. Overall, a  
89 thorough analysis of the correlation between metal contents and settling velocity and the importance  
90 of Fe have not been considered in previous work.

91 The objective of this article is to predict the spatial distribution of trace metal contamination through  
92 (i) the investigation of the correlation between metal contents (major element: Fe and some trace  
93 metals: Cr, Cu, Ni and Pb) in trapped sediments and their settling velocity in a stormwater detention  
94 basin, and (ii) the implementation of such correlations in a LDPM, taking into considerations the  
95 interactions between hydrodynamics and particle physico-chemical characteristics.

## 96 **2. Methods and materials**

### 97 *2.1. Experimental site and sampling locations*

98 Our work was conducted in the Django Reinhart stormwater detention basin (DRB), which remains  
99 dry during dry weather. The DRB is a part of the broader facilities investigated within the framework  
100 of the Field Observatory for Urban Water Management (or OTHU in French,  
101 <http://www.graie.org/othu/> - see also Zhu and Lipeme Kouyi, 2019). Fig. 1a provides a panoramic  
102 photograph of DRB, while its characteristics are presented in Table 1.

103 **Fig. 1. (a) Panorama of DRB, (b) hydrocyclone trapping system at the inlet 1 of DRB, (c) sketch**  
104 **of DRB and sampling points, (d) honeycomb-like sampling traps**

105 **Table 1. Characteristics of DRB**

106 Sediments were collected from six sampling sites, five of which are situated at the base of DRB (P01,  
107 P02, P04, P07, P12bis, illustrated in Fig. 1c). The sampling sites were selected according to sediment  
108 accumulation zones and previous studies (Sébastien et al., 2014b; Torres et al., 2007; Yan et al., 2014).  
109 Stormwater enters from the inlet situated at the lower-right side, and creates a counterclockwise swirl  
110 at the centre of the basin (shown in yellow in Fig. 2). There are then several flow paths within the  
111 basin (in orange, green, red and magenta in Fig. 2). Sampling points P01 and P02 are prone to trap  
112 medium-sized particles (median size D50 of 40 - 200  $\mu\text{m}$ ), given their locations near the basin inlet  
113 and at the middle of a flow path, respectively. Points P04 and P07 are situated at the end of the flow  
114 path where fine particulate particles (median size D50 of 25 - 70  $\mu\text{m}$ ) are expected to be trapped.  
115 Indeed, Jacopin et al. (1999) revealed the same trend i.e. the finest particles are found in the furthest  
116 part from the inlet of detention/retention basin. Point P12bis is a specific sampling site near a small  
117 tank designed to trap hydrocarbons, where medium and coarse particles are usually found (median  
118 size D50 of 200  $\mu\text{m}$ ). For each point, 3 honeycomb-like traps (Fig. 1d) were placed at the bottom. A  
119 hydrocyclone system was designed as a sampling device and installed at the inlet (illustrated in Fig.  
120 1b) in order to intercept particulate pollutants from the inlet of basin (Zhu et al., 2016).

121 **Fig. 2. Streamline of the liquid phase flow obtained by computational fluid dynamics**  
122 **simulations ( $Q = 0.35 \text{ m}^3/\text{s}$ , mean flow rate) and characteristics of sediments: (a) locations of**  
123 **settled particles of different sizes shown in different colors: red circles for coarse particles ( $D50 >$**   
124  **$500 \mu\text{m}$ ), yellow for medium ones ( $D50$  average  $40 \mu\text{m}$ ), and green for fine ones ( $D50$  average  $25$**   
125  **$\mu\text{m}$ ). (b) locations of different sampling sites (P01, P02, P04, P07, P12bis) at the base of DRB.**

126        2.2. Presentation of campaigns

127        Five campaigns were conducted during rain events in 2017 (from spring to winter). Nineteen sediment  
128        samples from 6 sites were collected and characterized (summarized in Fig. 3). The main  
129        characteristics of the sampled rain events and their corresponding hydraulic parameters in the  
130        detention basin are presented in Table 2.

131        **Fig. 3. Campaign timeline and sampling points for each campaign**

132        **Table 2. Characteristics of the sampled rain events and corresponding hydraulic parameters in**  
133        **DRB**

134        2.3. Methodology to predict distribution of trace metal contamination

135        2.3.1. Physical and chemical characterizations and determination of their correlation

136        In this study, particle-size distribution, settling velocity distribution and metal contents in sediments  
137        were analysed, according to the standards and protocols listed in Table 3.

138        **Table 3. Standard and protocols for physical and chemical analyses**

139        The VICAS protocol (a French acronym for Effluent Settling Velocity, Chebbo et al., 2009) is applied  
140        to measure settling velocity distribution. It is based on the principle of homogeneous suspension,  
141        where the solids are uniformly distributed over the entire sedimentation height. The measurement is  
142        realised with a plexiglas sedimentation column in the laboratory. The settled solids at a set of 10  
143        predefined time points (t = 1, 2, 4, 8, 16, 32min, 1, 2, 4, > 24h) are manually collected at the bottom  
144        of the sedimentation column in aluminium receptacles. The evolution of accumulated mass of settled  
145        particles over time is then determined by measuring the mass in each receptacle, which yields the



146 settling velocity distribution curve. Meanwhile, the average settling velocity in each receptacle  
147 defined in Eq. 1 is used to investigate the correlation between metals contents and settling velocity:

$$V_s = \frac{H}{t} \quad \text{Eq. 1}$$

148 where  $V_s$  denotes particle settling velocity (mm/s),  $H$  is water height in the sedimentation column  
149 (mm) and  $t$  is the time point (s) when the receptacle with collected particles is removed.

150 Metals contents in particles are then analysed with ICP-OES (inductively coupled plasma optical  
151 emission spectrometry) method. The total suspended solids (TSS) are filtered through glass fibre  
152 filters (0.45  $\mu\text{m}$ ) and dried at 105 °C (French standard NF EN 872, 2005). Mineralization is then  
153 applied in order to extract soluble elements from particles with aqua regia (NF EN 16174, 2012). The  
154 obtained solution is finally diluted to 50 ml, filtered at 0.45  $\mu\text{m}$  and analysed with ICP-OES  
155 equipment. For each element, the limit of detection (LOD) is calculated from the calibration. The limit  
156 of quantification (LOQ) is considered to be 3.3 times of LOD. In our study, as a precaution, only the  
157 values larger than 3 times of LOQ were considered as quantifiable.

158 Fig. 4 shows the methodology of physical and chemical characterizations. Two groups of data  
159 (physical and chemical characteristics) were gathered from the collected samples, in order to,  
160 respectively, (i) obtain overall physical and chemical characterization of samples and associated  
161 global relationships and (ii) reveal in particular the correlation between metals contents and settling  
162 velocity, as well as its significance. The first group (Data of group I) consists of particle-size  
163 distribution, settling velocity distribution and metal contents (Fe, Cr, Cu, Ni and Pb) of 19  
164 sub-samples (deriving from the 19 original samples). The second group (Data of group II) consists of  
165 settling velocities and metals contents (Fe, Cr, Cu, Ni and Pb) of 190 sub-samples under the VICAS

166 protocol. For each of the 19 samples, 10 sub-samples, i.e. receptacles of particles removed from the  
167 bottom of experimental column at all the 10 predefined time points  $t$ , have different settling  
168 velocities (described by Eq. 1). For each receptacle, metal contents in collected sediments are  
169 measured.

#### 170 **Fig. 4. Methodology of physical and chemical characterizations**

171 Several statistics have been computed, including: (i) principal components of physical and chemical  
172 characteristics of group I via PCA (Principal Component Analysis), (ii) correlation between metals  
173 contents and settling velocity based on the data of group II and test of significance, and (iii)  
174 correlation matrix for all metals accounting for data of group II. In this study, Spearman's rank  
175 correlation coefficient is applied as the settling velocities are not normally distributed according to the  
176 Shapiro-Wilk test (Shapiro and Wilk, 1965) and a monotonic relationship is observed between metal  
177 contents and settling velocity. Significance tests of correlation coefficient are also carried out by  
178 comparing  $p$ -value to a significance threshold (denoted as  $\alpha$ , equal to 0.05 by default). Bonferroni  
179 correction (Dunnett, 1955) is applied to reduce false positive (Type I) errors when multi-comparisons  
180 are applied. In order to set FWER (Family-wise error rate) lower than  $\alpha$ , it rejects the null hypothesis  
181 with  $p - value$  as follows:

$$p - value \leq \frac{\alpha}{m} \quad \text{Eq. 2}$$

182 where  $m$  is the total number of null hypotheses.

#### 183 2.3.2. Strategy to combine derived correlations with LDPM

184 LDPM was employed to simulate sediment transport in DRB (Yan et al., 2014). The flow was firstly  
185 simulated in steady state condition and then used as a base for further sediment transport modelling with a  
186 Lagrangian approach. The model was evaluated and had a good fit with both *in situ* free surface velocity  
187 field measurement results (Zhu et al., 2019) and measured accumulated sediment distribution at the bottom  
188 of DRB (Yan et al., 2014). LDPM approach allows the computation of particles trajectories. The  
189 interaction between sediments and the bottom wall was modelled by an original boundary condition based  
190 on turbulent kinetic energy threshold (Yan et al., 2014). During LDPM simulations, the location in the  
191 DRB as well as the physical characteristics (settling velocity, particle size and density) of sediments was  
192 recorded. The focus was placed on the settled particles as they represent accumulated sediments or deposits  
193 in the DRB. The metals contents distributions were then computed by combining the correlation between  
194 metals contents and settling velocity with recorded simulated data deriving from LDPM approach.

### 195 **3. Results**

#### 196 *3.1. Physical and chemical characteristics from data of group I*

197 Physical and chemical characteristics are illustrated in Table 4. In general, settling velocity varies with  
198 campaign and site, consistent with previous work (e.g. Torres et al., 2007). The samples collected  
199 from the inlet show the most significant temporal variability, with median settling velocity ranging  
200 from 1.9 to 11.6 m/h. Trapped particles from P01 have higher settling velocities than those from the  
201 other sampling sites at the base of DRB. Indeed, the location P01 is near the inlet where heavy  
202 particles settle rapidly, as demonstrated e.g. by Jacopin et al. (1999).

203 As illustrated in Table 4, Fe contents are at least 36 times higher than Cu contents and up to 200 times  
204 higher than the other trace metals contents (Cr, Ni and Pb). As for trace metals, Cu, Ni and Pb

205 contents exceed the target values of Dutch standards (DTIV, 2000). Cu contents, as well as Pb  
206 contents in some cases, surpass even the intervention threshold. It is noticed that Fe contents at the  
207 inlet are lower (average 16.9 g/kg DM) than those observed in the basin (average 20.7-23.9 g/kg DM),  
208 in opposition to trace metals. Besides, samples collected from the inlet show a significant temporal  
209 variability, with a coefficient of variation of approximately 50%.

210 Fig. 5 shows PCA results of all physical and chemical variables (particle size, settling velocity and  
211 metals contents). Principal component 1 (PC1) explains 48.9% of variance, while PC2 explains 22.9%.  
212 Overall, settling velocities are highly related among themselves (V20, V50 and V80). The same  
213 conclusion can be drawn for particle sizes (D10, D50 and D90). The relationship among different  
214 metals, as well as that between metal contents and settling velocities or sizes, is unclear. Temporal  
215 variability is observed as expected. Event C3 is a storm of high rain intensity and maximum inlet flow  
216 rate but low total depth and rain duration. Event C4 is a rain event of the highest total depth and  
217 maximum water level in DRB. This may lead to strong variation of spatial distribution of sediments  
218 due to shear stress (Adamsson et al., 2003) or turbulence in DRB (Sechet and Le Guennec, 1999).  
219 Significant temporal variability is particularly observed for particles intercepted by the hydrocyclone  
220 device at the inlet of the basin. Among particles trapped at the base of DRB, those at P02 seem to be  
221 different from particles observed at other sites, characterized by their low settling velocities and high  
222 metal contents, regardless of the campaign. In fact, particles with high settling velocities tend to settle  
223 near the inlet (P01), while P02 is in the main recirculation zone with long residence time which  
224 enables particles to settle progressively (Zhu and Lipeme Kouyi, 2019).

225 **Table 4. Physical and chemical characteristics of trapped sediments**

226 **Fig. 5. Principal component analysis (PCA) of physical and chemical characteristics based on**  
227 **the data of group I**

228 *3.2. Correlation between metals contents and settling velocity, and correlation matrix for*  
229 *different metals based on data of group II*

230 All the results from different campaigns (C1-C5) and sampling sites (inlet, P01, P02, P04, P07 and  
231 P12bis) are presented in Fig. 6 (a-e) to analyse the correlation between metals contents and settling  
232 velocity. Fig. 6 (f-j) are boxplots of different metals contents with respect to settling velocity. In  
233 general, results show that contents of the metals in settled sediments are relatively stable, with values  
234 varying within ranges of 15-35 g/kg, 20-120, 200-650, 20-150 and 50-250 mg/kg DM for Fe, Cr, Cu,  
235 Ni and Pb, respectively, except for a few outliers. [Fe] and [Pb] have significant correlations with  
236  $\log(V_s)$  after Bonferroni correction, especially in the case of [Fe], with a correlation coefficient equal  
237 to -0.52. Higher [Fe] and [Pb] are related to lower settling velocity. The best fit of their correlations  
238 are illustrated in Fig. 6a and Fig. 6e and can be defined by the equation shown at the upper-right side.  
239 [Cu] tends to decrease slightly with the increasing of  $V_s$ , in opposite to [Cr]. Indeed, previous works  
240 suggest that Fe contents are relatively stable, while Cu can be variable in stormwater environment  
241 given its affinity with organic matter (Camponelli et al., 2010). No obvious correlation is observed  
242 between [Ni] and  $V_s$ . The dispersion around the regression line (marked as red dashed lines for 95%  
243 confidence interval) is related to spatio-temporal variabilities of metal contents and settling velocity  
244 distributions, physico-chemical processes and characteristics, as well as uncertainties in sampling and  
245 analytical measurements (Torres and Bertrand-Krajewski., 2008; Sébastien et al., 2015). The  
246 physico-chemical analyses conducted by Becouze-Lareure et al. (2018) show a high organic matter  
247 content for the trapped sediments in DRB. This may lead to changes in the physico-chemical

248 conditions in the sediments, which could affect the solubility and availability of certain trace metals.  
249 These different processes and assumptions have already been observed in various investigations  
250 focusing on urban sediments, such as those from rivers (Chapman et al., 1998) and from reservoirs  
251 (Frémion et al., 2016; Frémion et al., 2017). Torres et al. (2007) also showed the spatial and temporal  
252 variability of settling velocity of DRB sediments.

253 **Fig. 6. (a-e) Correlation between metals contents [M] in g/kg DM and settling velocity ( $V_s$ ) in**  
254 **mm/s based on data of group II; (f-j) Boxplot of different [M] with respect to each  $V_s$ .**

255 The correlation matrix among different metals contents is also calculated (shown in Fig. 7). Results  
256 show that almost all the studied metals have significant correlations with each other except for Cr  
257 versus Fe and Ni versus Pb. Fe and Pb are the most related metals, with a correlation coefficient of  
258 0.61.

259 **Fig. 7. Correlation matrix of different trace metals contents in trapped particles: the**  
260 **distribution of each variable is listed on the diagonal. The bivariate scatter plots with their**  
261 **linear fits are displayed below the diagonal. The upper triangle contains the correlation**  
262 **coefficients and their significance levels. Each significance level is associated to a symbol:**  
263  **$p$ -values of 0.001, 0.01, 0.05, 0.1 correspond to symbols of \*\*\*, \*\*, \* and ■, respectively.**

### 264 3.3. Prediction of trace metals contamination distribution

265 Given the significant correlations of Fe and Pb contents with settling velocity, the derived correlations  
266 (equation in Fig. 6) were applied on LDPM outputs to simulate the spatial distribution of Fe and Pb  
267 contents in DRB. Fig. 8 illustrates the comparison of the measured and simulated distribution of Fe  
268 and Pb contents at the base of DRB. The simulated [Fe] at P01, P02, P04 and P07 are consistent with

269 the measurements obtained from group I, where P07 and P02 have the highest [Fe] in sediments. P07  
270 shows a significant variation in [Fe]. Indeed, P07 is situated at the end of pathway, where sediments  
271 tend to be resuspended, as previous work has suggested (Zhu et al., 2017). In addition, P07 is near an  
272 orifice, which may lead to maximum flow shear and velocities around this site and through the orifice,  
273 increasing variability due to dispersion of sediments (e.g. interaction between burst and bedload  
274 transport, see e.g. Sechet and Le Guennec, 1999). Simulated [Pb] in DRB is around 129 mg/kg DM,  
275 which is not consistent with the measurements due to temporal variability. However, the results are  
276 consistent when comparing the simulated Fe contents distribution with the measured Pb contents at  
277 different sampling points. Indeed, significant positive correlation between Fe and Pb is revealed in Fig.  
278 7. Hence, it is interesting to use Fe as an indicator to predict other metals contents distribution.  
279 Uncertainties with 95% confidence interval of  $\pm 8.8$  g/kg and  $\pm 69.4$  mg/kg for Fe and Pb, respectively,  
280 are observed. In DRB, P02 and P07 are highly contaminated by Pb according to the analyses obtained,  
281 not only throughout this study, but also in many investigations carried over the last 10 years. For  
282 example, Becouze-Laureure et al. (2016) show that the areas farther from the inlet are more  
283 contaminated and that P02 presents highly contaminated sediments. The sediments at P02 and P07  
284 settle slowly, with a mean settling velocity of around 2 mm/s, explained by the two locations being  
285 remote from the inlet.

286 **Fig. 8. Comparison of measured and simulated Fe and Pb contents distribution: P01, P02, P04,**  
287 **P07 locations are coloured in blue, orange, black and red, respectively.**

## 288 4. Discussion

289 4.1. Use of Fe as indicator of pollution and for the prediction of contamination distribution

290 In this study, [Fe] in trapped sediments is strongly related to settling velocity and this relationship is  
291 relatively stable from one site to another and from one event to another. In addition, significant  
292 correlations between Fe and trace metals are observed (Fig. 7). Other studies have also observed  
293 positive correlations between Fe and Cr, Cu, Pb, Ni and Zn in highway stormwater runoff (Kayhanian  
294 et al., 2007). Drapeau et al. (2017) revealed a close link among Al, Fe and Si, as well as linear  
295 regression between Fe and Cu, Zn, P, S, Si and organic matter in a stormwater infiltration basin.  
296 Given the significant correlation between Fe and certain pollutants (here Pb and Cu), the simulated Fe  
297 content distribution can then be utilised to understand or to explain the distribution of other particulate  
298 pollutants that have affinities with Fe. Besides, iron isotopes have been widely used as tracers to  
299 analyse biochemical processes (e.g. metal transport, microbial redox reactions and transformation of  
300 organic matter-ferrihydrite coprecipitates), and track sources and other components such as suspended  
301 Fe-organic carbon aggregates (Gould et al., 2008; Ingri et al., 2018; Owens et al., 2012; Tishchenko et  
302 al., 2015). In DRB, P07 and P02 present the highest maximum values of [Fe] and are also highly  
303 contaminated areas given the significant positive correlation between Fe and certain trace metals.  
304 Hence, P07 and P02 should be the preferential zones for cleaning.

#### 305 4.2. Use of settling velocity for stormwater detention basin sediments management

306 Most studies on the correlation between particle physical and chemical characteristics in stormwater  
307 detention basins focus on the relationship between particle size (e.g. Kayhanian, 2012; Tuccillo, 2006)  
308 or sediment density (El-Mufleh et al., 2014) and trace metal contents. However, settling velocity  
309 should be emphasized given its relationship with other physical characteristics (Loch, 2001). It has  
310 been widely applied in urban stormwater management and its importance has been demonstrated



311 (Ciccarello et al., 2012; Yun et al., 2010). Settling velocity is also a key element, when combined with  
312 the residence time, for the sizing of stormwater detention basins.

313 The design and management of stormwater detention basins not only need knowledge of  
314 hydrodynamic behaviour, but also an understanding of the spatial distribution of highly contaminated  
315 sediments. Various modelling approaches (e.g. LDPM) can be used to address the understanding of  
316 the velocity field and the spatial distribution of sediment in stormwater detention basins (Adamsson et  
317 al., 2003). Given that the particulate fraction of certain metals and PAHs in stormwater from industrial  
318 catchments is above 60 % and 80 %, respectively (Becouze-Lareure et al., 2019) and most other  
319 pollutants are conveyed in particulate phase (Ashley et al., 2004), the investigation of the correlation  
320 between metal contents in sediments and settling velocity may support the coupling between chemical  
321 and physical aspects. The final simulation results help to predict pollutant deposition and determine  
322 the priority cleaning zones in stormwater detention basins. They may also be used as a support for the  
323 design of stormwater detention basins using trapping or removal efficiency as targeted criteria.

#### 324 4.3. Relationship between sediments' physical and chemical characteristics

325 The significant correlation between metal contents in sediments and their settling velocity is a key  
326 finding of this study. Badin et al. (2008) suggested that organic matter in urban stormwater sediments  
327 is related to grain size. Bernardin-Souibgui et al. (2018) found that *Nocardia* counts are positively  
328 linked to volatile organic matter. Wiest et al. (2018) revealed that BPA is associated with fine particles.  
329 Concerning the physical characteristics, we can analyse particle-size distribution, density and shape  
330 related to each fraction of settling velocity to understand their links with chemical characteristics.  
331 Given the strong correlation of Fe content with settling velocity, it is interesting to investigate more

332 thoroughly the oxidation states, isotopes of Fe and the related physical, chemical and biological  
333 processes, such as sorption and precipitation (Taylor and Kauhauser, 2011). Besides, other pollutants  
334 such as PAHs, organic matter and some pathogenic bacteria can be investigated to see if they are  
335 related to metals or settling velocity.

#### 336 4.4. Sediment management based on targeted dredging strategy

337 The methodology proposed in this article can be applied in any other stormwater detention or  
338 retention basin (dry or wet) constructed on a catchment (industrial, urban or periurban) in order to  
339 compare and evaluate deriving results against the obtained correlation in this study. This methodology  
340 also informs the intervention and treatment of sediments with a focus on the highly contaminated area.  
341 In general, the intervention criteria could be determined by comparing the metals contents to the  
342 Dutch target and intervention values (DTIV, 2000) and taking into account site specificities. The  
343 outcomes of this paper suggest that targeted dredging may be a good alternative for sediment  
344 management. In the case of DRB, P02 and P07 are highly contaminated and should be treated  
345 promptly. In theory, these contaminated sediments could be stored in places where less recirculation  
346 and sediment resuspension phenomenon occur (e.g. the upper-left side of DRB). Indeed,  
347 Becouze-Laureure et al. (2018) showed that the ecotoxicity level decreases over time and sediments  
348 should thus be left *in situ* before being discharged to a dedicated resource recovery plant or a  
349 separation device. Sediments from these most problematic zones could then be separated by means of  
350 screening and attrition (Petavy et al., 2009). As the focus is only placed on the problematic areas, less  
351 sediments need to be extracted and can be directly treated *in situ*. Such an approach could  
352 substantially reduce cost related to sediments transportation, treatment, and reuse.

353 **5. Conclusions**

354 Better understanding of the spatial distribution of trace metal contamination in stormwater detention  
355 basins is vital to better manage accumulated sediments and better design such facilities, taking into  
356 account the interactions between hydrodynamics and sediment physico-chemical characteristics. Our  
357 work investigated the locations of highly contaminated sediments with trace metals in a settling and  
358 detention basin by coupling a LDPM with the relationships of sediments' physico-chemical  
359 characteristics (correlation between Fe, Cr, Cu, Ni, Pb contents and settling velocity). Based on a  
360 large dataset, Fe and Pb contents have a significant correlation with settling velocity, followed by Cu  
361 and Cr. The observed significant correlation between Fe content and settling velocity remained stable  
362 for all campaigns and sampling sites. An equation describing this correlation is coupled with  
363 simulated spatial distribution of sediments to predict Fe content distribution. Obtained results are  
364 consistent with *in situ* measurements. Accounting for hydrodynamic behaviour (streamlines exhibiting  
365 recirculations, flow shear and turbulence characteristics), particles carrying Fe could then be tracked  
366 and used as an indicator to comprehensively identify trace metals contamination areas (e.g. deposition  
367 and resuspension zones). This may help to determine the priority cleansing zone in detention basins  
368 and better design the stormwater detention basin by taking into consideration all these correlations as  
369 well as hydrodynamic parameters in sediments transport equations.

370 **Acknowledgement**

371 This research is supported by OTHU (Observatoire de Terrain en Hydrologie Urbaine), La Métropole  
372 du Grand Lyon, ANR CESA CABRRES program (program grant 2011-CESA-012) and CSC  
373 Scholarship. In addition, this work was performed within the framework of the EUR H<sub>2</sub>O'Lyon

374 (ANR-17-EURE-0018) of Université de Lyon (UdL), within the program "Investissements d'Avenir"  
375 operated by the French National Research Agency (ANR). The authors are grateful to David Lebouil  
376 for ICP measurement, Dominique Babaud, Serge Naltchayan, Nicolas Walcker and Stéphane Vacherie  
377 for technical support. The authors would like also to thank Santiago Sandoval Arenas and Qiufang  
378 Zhan for scientific suggestions, Hexiang Yan for providing CFD model data, as well as Prof. Tim  
379 Fletcher (the University of Melbourne) and Bonan Cuan for English writing improvements.

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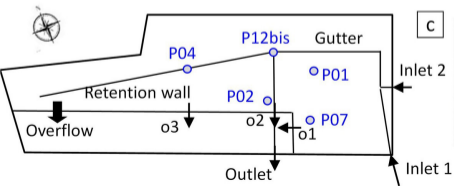
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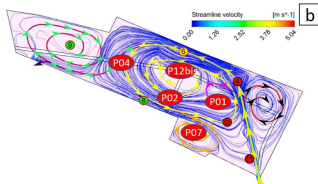
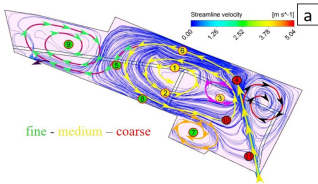
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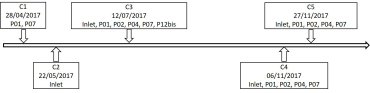
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## 19 Samples from 5 campaigns

Inlet (hydrocyclone system)



Bottom of basin (traps)



## Physical and chemical characterization

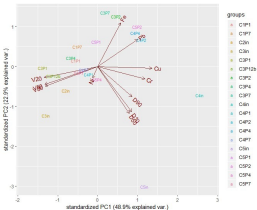
### Data of group I (19 sub-samples):

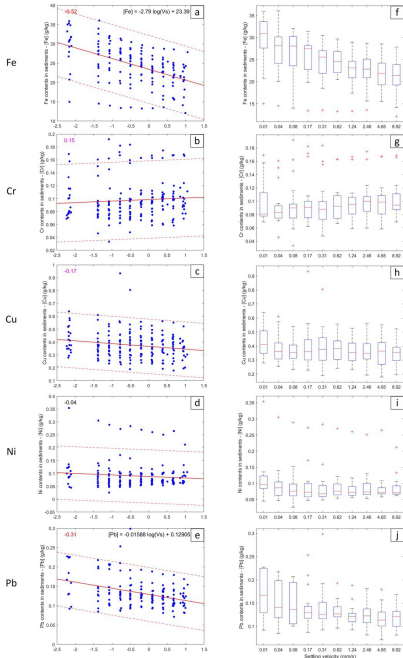
Particle-size distribution  
Settling velocity distribution  
Metals contents (Fe, Cr, Cu, Ni, Pb)

### Data of group II (190 sub-samples):

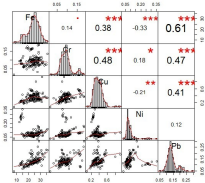
10 sub-samples for each of 19 samples,  
10 fractions of settling velocities

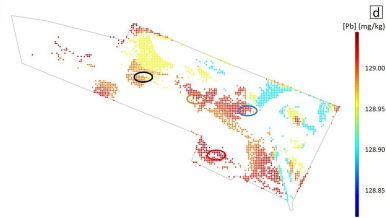
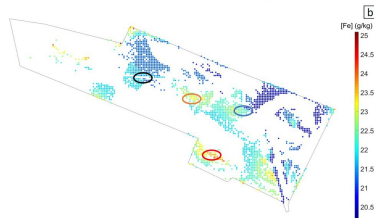
Metals contents (Fe, Cr, Cu, Ni, Pb) for each fraction of settling velocity





Parameters in (a-e)	Explanations
Correlation coefficient	Left-upper side in red (p -value < 0.05/190 according to Eq. 2 with Bonferroni correction) when the correlation is significant in magenta when p-value < 0.05.
Correlation equation	Right-upper side when the correlation coefficient is significant.
Correlation best fit	Least-squares error minimization, illustrated by red solid lines —
95% confidence interval	Illustrated by red dashed lines - - -





**[Fe] (g/kg DM)**

a (data of C3-C5 in group I)

b: uncertainty of  $\pm 8.8$  g/kg (95% confidence interval)

**[Pb] (mg/kg DM)**

c (data of C3-C5 in group I and previous campaign data by Becouze-Laureure et al. (2018))

d: uncertainty of  $\pm 69.4$  mg/kg (95% confidence interval)

**Measured [M] at P01, P02, P04 and P07:** minimum, averaged and maximum values are plotted, respectively.

**Simulated median [M] spatial distribution at the bottom of DRB**

Table 1. Characteristics of DRB

Type of characteristics	Characteristics
Location	Chassieu, France
Type of drainage system	Separated stormwater drainage system
Watershed type	Industrial watershed of 185 ha
Impervious rate of the watershed	75%
Bottom surface area	11 000 m <sup>2</sup>
Storage capacity	32 000 m <sup>3</sup>
Max outlet flow rate limit	0.35 m <sup>3</sup> /s (Bardin and Barraud, 2004)
Materials	Bottom in bitumen and banks covered with plastic lining
Compositions	2 inlets (mainly inlet 1 operates, illustrated in Fig. 1b), an outlet, a gutter guiding the flow to 3 orifices during dry periods and an overflow when the water height exceeds the retention wall (presented in Fig.1 c).
Construction and maintenance	Built in 1975, rehabilitated in 2002, cleaned in 2006 and total sediment removal in 2013.

Table 2. Characteristics of the sampled rain events and corresponding hydraulic parameters in DRB

Campaign date	C1	C2	C3	C4	C5
	28/04	22/05	12/07	06/11	27/11
<i><u>Rainfall characteristics</u></i>					
Rain Duration (hour:min)	19:22	08:14	03:02	18:26	16:28
Total Depth (mm)	26.5	17.5	10.5	30.9	11.2
Mean Intensity (mm·h <sup>-1</sup> )	1.4	2.1	3.4	1.7	0.7
Max intensity (mm·h <sup>-1</sup> )	6	7.5	58.2	11.7	6.9
<i>ADWP</i> (days)	23	4	8	12	11
<i><u>DRB hydraulic parameters</u></i>					
Mean inflow rate (m <sup>3</sup> /s)	0.21	0.31	0.24	0.31	0.11
Max inflow rate (m <sup>3</sup> /s)	0.76	0.81	1.27	1.08	0.77
Max water level (m)	0.51	0.54	0.39	0.69	0.50

*ADWP*: antecedent dry weather period

Table 3. Standard and protocols for physical and chemical analyses

Analysis	Method	Standard
Particle-size distribution	Mastersizer 2000 laser diffraction granulometer	NF ISO 13320-1 (2000)
Settling velocity distribution	VICAS protocol (Chebbo et al, 2009)	
Metal content	ICP-OES	NF EN ISO 11885 (1998)



Table 4. Physical and chemical characteristics of trapped sediments

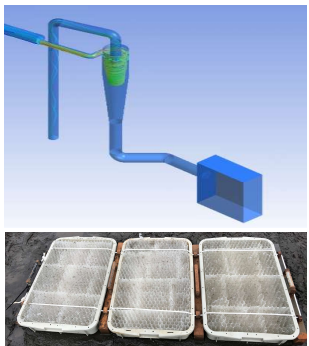
Sample	D50 ( $\mu\text{m}$ )	V50 (m/h)	Fe contents	Trace metals contents (mg/kg)					
			(g/kg)	Cr	Cu	Ni	Pb		
C1	P01	69.2	7.0	nm	74.3	360.1	56.7	98.8	
	P07	54.5	6.6	nm	78.3	325.7	54.1	114.3	
C2	inlet	55.6	6.7	13.5	96.5	222.0	237.7	99.8	
C3	inlet	313.5	11.6	18.2	71.5	242.3	85.2	114.1	
	P01	52.9	9.6	20.4	73.5	233.5	74.6	105.7	
	P02	37.7	3.4	nm	nm	nm	nm	nm	
	P04	45.3	6.9	nm	nm	nm	nm	nm	
	P07	45.5	4.1	27.5	93.1	278.8	93.9	137.1	
	P12bis	78.3	7.5	15.4	62.7	226.8	70.5	95.8	
	mean	95.5	7.2	20.4	75.2	245.4	81.1	113.2	
	stdv	107.7	3.2	5.2	12.8	23.1	10.6	17.6	
	C4	inlet	nm	1.9	21.0	154.3	584.4	93.8	200.6
		P01	144.6	5.9	18.7	76.3	308.7	58.1	96.7
P02		199.3	2.9	25.6	96.4	457.4	68.7	136.6	
P04		129.4	2.6	24.4	80.5	428.2	61.9	140.7	
P07		79.8	6.7	17.9	89.6	355.3	63.1	111.5	
mean		138.3	4.0	21.5	99.4	426.8	69.1	137.2	
stdv		49.2	2.2	3.4	31.7	105.9	14.3	39.8	
C5	inlet	870.5	4.3	14.9	110.4	429.0	80.4	69.7	

	P01	78.5	6.0	24.7	94.9	349.2	65.7	115.7
	P02	100.2	2.1	22.2	89.1	378.3	72.7	167.2
	P04	433.3	5.4	21.1	65.8	258.1	59.2	112.3
	P07	109.8	5.7	16.6	66.3	275.0	42.7	88.9
	mean	318.5	4.7	19.9	85.3	337.9	64.1	110.8
	stdv	341.6	1.6	4.0	19.2	71.4	14.4	36.6
inlet	mean	413.2	6.1	16.9	108.2	369.4	124.3	121.1
	stdv	416.5	4.2	3.4	34.7	170.9	75.8	56.2
P01	mean	86.3	7.1	21.3	79.7	312.9	63.8	104.2
	stdv	40.3	1.7	3.1	10.1	57.3	8.2	8.6
P02	mean	112.4	2.8	23.9	92.8	417.8	70.7	151.9
	stdv	81.5	0.6	2.4	5.1	55.9	2.9	21.6
P04	mean	202.7	5.0	22.7	73.2	343.2	60.5	126.5
	stdv	204.1	2.2	2.4	10.4	120.3	1.9	20.1
P07	mean	72.4	5.8	20.7	81.8	308.7	63.5	113.0
	stdv	28.9	1.2	6.0	12.1	38.7	22.0	19.7

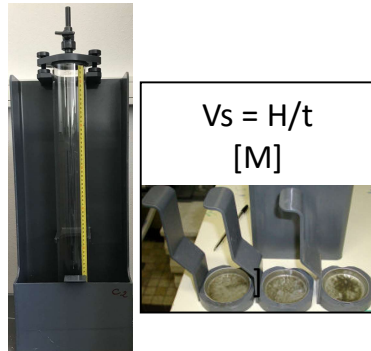
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D50: median particle size, V50: median settling velocity, nm: not measured, stdv: standard deviation

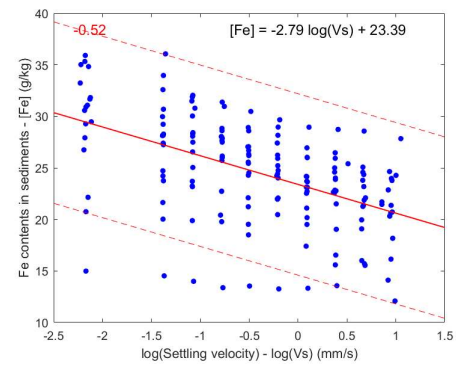
### Sampling



### Characterization



### Correlation



### Contamination distribution

