A new approach of monitoring and physically-based modelling to investigate urban wash-off process on a road catchment near Paris

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Abstract
Nowadays, the increasing use of vehicles is causing contaminated stormwater runoff to drain from roads. The detailed understanding of urban wash-off processes is essential for addressing urban management issues. However, existing modelling approaches are rarely applied for these objectives due to the lack of realistic input data, unsuitability of physical descriptions, and inadequate documentation of model testing. In this context, we implement a method of coupling monitoring surveys with the physically-based FullSWOF (Full Shallow Water equations for Overland Flow) model (Delestre et al., 2014) and the process-based H-R (Hairsine-Rose) model (Hairsine and Rose, 1992a, 1992b) to evaluate urban wash-off process on a road catchment near Paris (Le Perreux sur Marne, Val de Marne, France, 2661 m²). This work is the first time that such an approach is applied for road wash-off modelling in the context of urban stormwater runoff. On-site experimental measurements have shown that only the finest particles of the road dry stocks could be transferred to the sewer inlet during rainfall events, and most Polycyclic Aromatic Hydrocarbons (PAHs) are found in the particulate phase. Simulations over different rainfall events represent promising results in reproducing the various dynamics of water flows and sediment transports at the road catchment scale. Elementary Effects method is applied for sensitivity analysis. It is confirmed that settling velocity (\(V_s\)) and initial dry stocks (\(S\)) are the most influential parameters in both overall and higher order effects. Furthermore, flow-driven detachment seems to be insignificant in our case study, while raindrop-driven detachment is shown to be the major force for detaching sediment from the studied urban surface. Finally, a multiple sediment classification regarding the Particle Size Distribution (PSD) can be suggested for improving the model performance for future studies.

1. Introduction

It is predicted that by 2050, 64% of the “developing world” and 86% of the “developed world” will be urbanized (Montgomery, 2008). This trend of rapidly increasing urbanization requires better understanding of the urban wash-off phenomenon in order to develop more advanced management strategies.

Among the various substances of urban stormwater pollutants, suspended solids, heavy metals and Polycyclic Aromatic Hydrocarbons (PAHs) are widely considered as the major causes of contamination in receiving environments (Fletcher et al., 2013; Zoppou, 2001). Most of these heavy metals and PAHs are found in the particulate phase and associated with fine particles (Aryal et al., 2010; Bressy et al., 2012; Gasperi et al., 2014). Therefore, the studies of stormwater quality can focus on the urban sediment transport during stormwater events.

Numerous urban stormwater quality models exist, however, most of them are still unable to adequately reproduce urban wash-off dynamics (Dotto et al., 2012; Egodawatta et al., 2007; Elliott and Trowsdale, 2007). One of the major reasons is the lack of available and reliable local data. According to Duncan (1995); Vaze and Chiew (2003), accurate urban stormwater quality models require detailed spatial and temporal data of rainfall intensity, water runoff characteristics and pollutants’ features (e.g. Weight, Size, Settling velocity). Since it is impossible to collect sufficient water runoff data over different temporal and spatial points of an urban catchment, the application of Full Shallow-Water equations with extremely high-resolution topographic data is a promising approach.
approach for representing stormwater runoff processes (Grayson et al., 1992a, b). Another challenge of modelling urban stormwater quality is the shortage of physical descriptions of pollutant wash-off mechanisms. Until now, current urban wash-off models are generally based on exponential wash-off functions (e.g. SWMM, M-QUAL, HSPE, STORM etc.), assuming the rate of particle loss on a catchment scale is directly proportional to the availability of the pollutants on the road surface and to the water flow. With these equations, urban spatial heterogeneities are neglected, leaving models to rely on extensive calibration of empirical wash-off coefficients, a fact that limits their predictive capacities (Tsihrintzis and Hamid, 1997). Thus, greater insight into the physical processes of particulate detachment and transport will provide a more detailed understanding of the movement of pollutants in urban landscapes.

Only very few studies have been performed for the physically-based modelling of urban wash-off processes. Shaw et al. (2006) proposed a saltation-type wash-off model in which particles were repeatedly detached from the impervious surface by raindrop impacts and were transported laterally by overland flow while settling back to the surface. Massoudieh et al. (2008) presented a wash-off model in which detachment and reattachment of contaminants were considered as rate-limited processes and the detachment rate was assumed to be a function of flow velocity by a power expression. These existing models have provided a basic perception of developing new mechanistic wash-off models for urban surfaces. However, the wash-off processes in the above models were not combined with two-dimensional water-flow simulations, and the detachments were only represented by single effects of raindrop impacts (Shaw et al., 2006) or flow power influences (Massoudieh et al., 2008). These inadequate assumptions limit the reliability of such physically-based models for stormwater quality modelling in urban areas (Deletic et al., 1997; Dotto et al., 2012; Wijesiri et al., 2015).

In this study, the Hairsine-Rose (H-R) model (Hairsine and Rose, 1992a, b) coupled with the FullSWOF (Full Shallow-Water equations for Overland Flow) modelling system (Delestre et al., 2014; Le et al., 2015) is applied. Unlike other physically based approaches, the H-R model calculates raindrop-driven detachment, flow-driven detachment and deposition processes separately, with the net outcome being the difference between these process groups. The H-R model also simulates a deposited layer that differs from the original soil in its composition and detachability, which allows us to distinctively model urban dust and road pavement.

This study is the first time that the H-R model is applied and analyzed within the context of urban stormwater wash-off, using the example of a road catchment near Paris. With this new approach, our objective is to examine urban surface wash-off dynamics for several stormwater events. This approach couples detailed monitoring surveys and physically-based modelling, which may help to advance the understanding of stormwater wash-off mechanisms. The following sections will provide details on monitoring surveys for the road catchment, model configurations, and sensitivity analysis.

2. Materials and methods

2.1. Study site

A small urban road catchment near Paris (Le Perreux sur Marne, Val de Marne, France), including a segment of high traffic volume (more than 30,000 vehicles per day) and its adjacent sidewalk and parking zones, are selected for this study. A gutter is located between the road and the sidewalk, allowing water flow from the upper part of the catchment to the sewer inlet (Fig. 1). The total surface of the study basin is 2661 m², where approximately 65% of the surface are roads, 30% are sidewalks, and 5% are gutters and parkings. The western section on a higher incline than the eastern side, with an average slope of less than 2%.

2.2. On-site monitoring and sampling

2.2.1. Rainfall measurements

A tipping-bucket rain gauge is installed on the roof of a building close to the road catchment (less than 150 m). The pluviometer has a resolution of 0.1 mm. As the study area is quite small, rainfall is considered as homogeneous within the basin. Monitoring took place between September 20, 2014 and April 27, 2015, identifying different rainfall events by intervals longer than 90 min between two tipping records and total rainfall depth of each event of more than 1 mm. It has to be noted that there is no street sweeping on the study road, thus the antecedent dry days between two rainfall events are the only factor that influence the deposited dry stocks.

2.2.2. Monitoring at the sewer inlet

The sewer inlet is equipped for continuous monitoring of discharge, turbidity and ability to perform samplings for the analysis of particulate size distribution (PSD) and the PAHs features (Fig. 2a). The flow is measured by a Nivus Flowmeter, using the cross correlation method in order to calculate flow speed for different layers in a full pipe, which increased the reliability of data. The water discharge is recorded with a 1 min time interval inside the road inlet. At the same time, a multi-parameter probe (mini-probe OTT) is installed with the flowmeter, measuring turbidity with a 1 min time interval. For several rainfall events, a peristaltic pump (Watson Marlow) pumped 250 mL of water at regular volume intervals entering the inlet for the purpose of measuring mean TSS concentrations at the scale of rainfall event. The sampling bottles are located in a cabinet at the side of the road (Fig. 2b). The complete monitoring system is presented in Fig. 2c. The TSS-Turbidity relationship is therefore established based on samplings during 16 studied rainfall events, which follows a linear regression $TSS = 0.8533 \times$ Turbidity, with the $R^2$ equal to 0.97.

2.2.3. Road dust sampling

In the framework of the ANR (French National Agency for Research) Trafpollu project, the road dust sampling was carried out on the October 14th, 2014. The detailed experimental protocol is described in Bechet et al. (2015). The samples were collected in dry-weather after a dry period of 2 days. A two-square meter surface was delimited with adhesive tape. After hand-brushing the surface, the road dust was dry-vacuumed using a vacuum cleaner (Rowenta ZR80) (Fig. 3b). Road dust samples were collected in paper filters along the road: on the sidewalk, in the gutter and on the road (3 positions (noted as A, B, C) over 3 locations (marked as 1, 2, 3)).

2.3. Particle Size Distribution (PSD) analysis

For both dry samples (road dust) and wet samples (sewer inlet), particle size analysis is performed using a laser diffractometer for the fraction below 2 mm (Malvern® Mastersizer 3000), while the volume distribution is calculated with the Mie (1908) light scattering theory. In order to compare the mass distribution of dry deposits and suspended solids in the stormwater, the total mass of either road dust or TSS load for the entire catchment is calculated independently. Assuming the uniform distribution of sediments throughout the road surface, the measurements of the deposit samples (2 m²) are used to calculate the total mass of road dust on the catchment surface (2661 m²). Likewise, the total mass of loaded TSS during a rainfall event can be calculated by multiplying the
**Fig. 1.** Study area at Eastern Paris, France. The catchment is delineated by red dashed lines, the sewer inlet is located at the northeast side of the catchment. In this picture, road area is marked as grey, gutter area is marked as white, sidewalk and parking areas are marked as brown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Fig. 2.** (a) Monitoring equipments inside the sewer inlet; (b) Cabinet at the road side; (c) Flowchart of the monitoring system.

**Fig. 3.** (a) Location of sampling points along the road (Le Perreux, France); (b) road dust dry sampling by a vacuum cleaner in gutter (point 3).
measured mean TSS concentration by the total volume of flow water for each event.

2.4. PAH chemical analysis

Particles are freeze-dried during 48 h and then extracted by means of microwave-assisted digestion (Multiwave 3000, Anton Paar). PAHs samples are extracted using Methylene chloride/ Methanol (90/10, v/v) and spiked with similar surrogate standards over a 30 min cycle. Extracts are recovered by filtration, then the solvent is removed and the residue dissolved in 300 µl heptane before purification. Thus, a 2.1 g silica column is conditioned with 4 ml heptane and the PAH fraction is eluted with 10 ml heptane/ methylene chloride (80/20, v/v). 13 types of PAHs are analyzed with cation. Thus, a 2.1 g silica column is conditioned with 4 ml heptane and the PAH fraction is eluted with 10 ml heptane/ methylene chloride (80/20, v/v). 13 types of PAHs are analyzed with the accurate simulation of water for each event.

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2.5. High resolution topographic data

The accuracy of a process-based wash-off model depends on the accurate simulation of water flows. Therefore, precisely monitored topographic data should be adapted to the study site. In the framework of the ANR-Trafipollu project, topographic data of 1 cm-resolution was collected by an on-vehicle LiDAR by the National Institute of Geography of France (IGN) (Hervieu and Soheilian, 2013; Paparoditis et al., 2012). In order to have the model apply with an adequate number of grid cells (pixels), an aggregation of 1 cm-resolution to 10 cm-resolution is performed (Fig. 4).

![Topographic data](image)

**Fig. 4.** Topographic data of 10 cm-resolution for the model, (pixels 1833 × 515).

2.6. Model description

2.6.1. Water quantity modelling

The C++ code FullSWOF (Delestre et al., 2014) is applied for the water flow modelling in this study. The FullSWOF model uses a finite volume scheme to solve bidimensional Shallow-Water (SW) equations with topographical and friction source terms. The water infiltration process is represented by using the Green and Ampt model. Recently Le et al. (2015), recalled the studies of Heng et al. (2009), Kim et al. (2013), and introduced a faster numerical scheme for coupling the Hairsine-Rose (H-R) model with SW equations. These authors introduced a numerical scheme for coupling the H-R model with SW equations within the FullSWOF system, allowing the simulation of soil erosion and transport processes of sediments.

2.6.2. Wash-off modelling

In this study, it is supposed that sediments are represented by a single class of particles. This assumption is linked to experimental results obtained from urban dust analysis, which will be explained in the section below. This simplification greatly reduces the model complexity.

The H-R model allows particles to be present in one of three compartments: the flow itself (in the form of suspended solid), the deposited layer, or the original soil. Once sediments have been detached, particles can be suspended or return to the bed by deposition, forming a deposited layer from which they can be subsequently re-detached. Two types of wash-off processes are considered: the first one is due to rainfall impact; and the second one is due to the shear stress by overland flow. This presumption allows model to distinguish between the rates of detachment of the original cohesive soil and non-cohesive deposited sediments. In the case of urban catchment, the road asphalt is considered as a non-erodible original soil, while the road dust is the deposited layer. This consideration leads to a simplification of the initial H-R model by neglecting the terms of detachment on original soil (e, r). The processes represented in H-R model are illustrated in Fig. 5:

The H-R model reflects the conservation of mass entering and exiting a cell, equations are written as below (1–2):

\[
\frac{\partial c}{\partial t} + \frac{\partial q_c}{\partial x} = e_r + r_r - d
\]

(1)

\[
\frac{dm}{dt} = d - e_r - r_r
\]

(2)

where c represents the TSS concentration in mass per unit volume; m refers to the deposited sediment mass per unit area; \( e_r \) and \( r_r \) means the rate of rainfall-driven and flow-driven detachment for deposited layer, respectively; \( h \) is the water-height and \( q \) is water flux which are computed from the SW equations; and \( d \) is the deposition. The terms \( e_r, r_r \) and \( d \) can be written by Eqs. (3)–(5):

\[
e_r = a_dp
\]

(3)

\[
r_r = \frac{\Omega_e}{\rho_s \rho_w} gh
\]

(4)

\[
d = \nu_s c
\]

(5)

where,

- \( a_d \) is the detachability of the deposited sediment (kg m\(^{-3}\));
- \( P \) is the rainfall intensity (m/s);  
- \( \Omega_e \) is the effective stream power (W/m\(^2\)); 
- \( \rho_s \) and \( \rho_w \) are the densities of sediment and water (kg/m\(^3\)); 
- \( h \) is the water-height (m); 
- \( g \) is the standard gravity (m/s\(^2\)); 
- \( \nu_s \) is the settling velocity of the single-class particle in water (m/s).

According to Eq. (3), the rate of rainfall detachment \( e_r \) is considered to be dependent on rainfall rate \( P \). In Eq. (4), since the cohesive strength of the deposited sediment is considered negligible, the resisting force of flow-driven detachment only depends on the immersed weight of sediments. The power expended in lifting the sediment to some height in the flow is directly calculated by the rate of change of potential energy of the sediment. The detachability \( a_d \) and the effective stream power \( \Omega_e \) can be written as Eqs. (6)–(8):

\[
\text{According to Eq. (3), the rate of rainfall detachment (} e_r \text{) is considered to be dependent on rainfall rate (} P \text{). In Eq. (4), since the cohesive strength of the deposited sediment is considered negligible, the resisting force of flow-driven detachment only depends on the immersed weight of sediments. The power expended in lifting the sediment to some height in the flow is directly calculated by the rate of change of potential energy of the sediment. The detachability } a_d \text{ and the effective stream power } \Omega_e \text{ can be written as Eqs. (6)–(8):}
\]
This principle was originally proposed by Mutchler and Hansen with the rise in rainfall-driven and flow-driven detachment for original soil, respectively; \( e \) and \( r \) mean respectively the rate of rainfall-driven and flow-driven detachment for the deposited layer; and \( d \) is the rate of TSS deposition from the water flow to the deposited layer.

\[
a_d = \begin{cases} 
    a_{d0}, & h \leq h_0 \\
    a_{d0} \left( \frac{h_0}{h} \right)^b, & h > h_0 
\end{cases}
\]

where:

- \( a_{d0} \) is the initial detachability of deposited sediment (kg m\(^{-3}\));
- \( h_0 \) is the threshold of flow depth, above which the detachability will decline (m);
- \( b \) is a positive constant.
- \( F \) is the effective fraction of excess stream power;
- \( \Omega \) is the calculated total stream power (W/m\(^2\));
- \( \Omega_0 \) is the threshold stream power below which there is no entrainment (W/m\(^2\));
- \( S_f \) is the friction slope which is calculated by Manning’s equations;

Eq. (6) illustrates that the raindrop impact detachability declines with the rise in flow depth when it is beyond a certain threshold. This principle was originally proposed by Mutchler and Hansen (1970), and revised by Proffitt et al. (1991) for the H-R model. Eqs. (7) and (8) show that the rate of flow-driven detachment is due to the effective stream power \( \Omega_e \), while the source and sinks of stream power in overland flow are shown in Fig. 6.

2.7. Model performance and sensitivity analysis

2.7.1. RMSD and PCC objective functions

Model’s ability to replicate the TSS concentrations is first evaluated by the widely used Root-Mean-Square-Deviation objective function (RMSD) (Eq. (9)):

\[
RMSD = \sqrt{\frac{\sum_{t=1}^{n} (\text{Sim}_t - \text{Obs}_t)^2}{n}}
\]

where \( n \) is the total duration of the simulated rainfall duration, \( \text{Sim}_t \) and \( \text{Obs}_t \) are the simulated and observed TSS concentration at \( t \)-th minute.

However, Bennett et al. (2013), Gupta et al. (2009) summarized that when using the RMSD and its related Nash-Sutcliffe efficiency (NSE) criterion, the bias between the simulated and measured signals are systematically over-weighted, while the variability and the relative correlation are underestimated. Consequently, the RMSD coefficient assigns more importance to the highest TSS values, which have the most significant discrepancies between measurements and simulations, compared to other moderate fluctuations. As for the urban wash-off phenomenon, the first TSS concentration peaks are typically much more important than subsequent peaks, thus, using only the RMSD objective function could not truly evaluate the model’s performance on the overall TSS dynamics. In this case, we introduced the Pearson’s Correlation Coefficient (PCC) objective function as a complement (Eq. (10)):

\[
PCC_T = \frac{\sum_{t=1}^{T} (\text{Sim}_t - \overline{\text{Sim}}) (\text{Obs}_t - \overline{\text{Obs}})}{\sqrt{\sum_{t=1}^{T} (\text{Sim}_t - \overline{\text{Sim}})^2} \cdot \sqrt{\sum_{t=1}^{T} (\text{Obs}_t - \overline{\text{Obs}})^2}}
\]

where \( T \) indicate T-th minute in the duration of the rainfall event, \( \text{Sim}_t \) and \( \text{Obs}_t \) are the simulated and observed TSS concentration at \( t \)-th minute. \( \overline{\text{Sim}} \) and \( \overline{\text{Obs}} \) are the mean simulated and observed TSS concentration.

2.7.2. The investigated parameters

Generally, the simplified H-R model needs to define three parameters concerning the raindrop impact detachment \( \{a_{d0}, h_0, b\} \), two parameters involving the flow-driven detachment \( \{F, \Omega_0\} \), and two physical properties which are difficult to measure accurately \( \{V_s, S_f\} \).

Following Mutchler and Hansen (1970), most researchers (Heng et al., 2011; Proffitt et al., 1991; Torri et al., 1987) consider that \( h_0 = 0.33 \ D_h \), where \( D_h \) is the mean raindrop size. We use the same presumption in this study, with \( D_h = 2 \text{ mm} \) for the Parisian region in France (Gloaguen and Lavergnat, 1995), the parameter is hence fixed as \( h_0 = 0.7 \text{ mm} \).

As for the parameters \( a_{d0}, b, F, \) and \( \Omega_0 \), their testing ranges are determined by following the investigations of Beuselinck et al.
(2002), Heng et al. (2011), Hogarth et al. (2004), Jomaa et al. (2010), Profitt et al. (1991). These authors have investigated the optimized parameter values of the H-R model for several case studies. Although these parameter studies are based on erosion processes in natural soils, the physical interpretations of the indicated 4 parameters are related to the properties of sediment particles and water flows. Therefore, we could learn from the previous findings in order to set testing parameter ranges for urban wash-off modelling.

The settling velocity ($V_s$) and the initial dry stock ($S$) are roughly estimated from the measured data. As it is difficult to obtain the exact values of these parameters, we make some assumptions from the observed values, which will be explained in the section below. The testing ranges of the 6 parameters are listed in Table 1.

### 2.7.3. Using Elementary-Effects (EE) method for sensitivity analysis

The Elementary-Effects (EE) method (also known as Morris method) is applied for the Sensitivity Analysis (SA) (Campolongo et al., 2007; Morris, 1991). The major advantage of this screening method is that it has a lower computational cost compared to other global SA methods (Song et al., 2015). Thus the EE method is particularly suited for computationally expensive models such as the physically-based FullSWOF platform.

With the EE method, parameters are sampled using One-At-a-Time (OAT) design (Saltelli and Annoni, 2010). Each model input $X_i$, $i = 1, ..., k$, is assumed to vary across $p$ selected levels in the parameter ranges. The parameter sampling space $\Omega$ is thus a k-dimensional p-level grid. Following a standard practice in sensitivity analysis, factors are assumed to be normalized in $[0,1]$ for generating parameter samples, and then transformed to their actual values for simulations. For a given $X = (x_1, x_2, ..., x_k)$, the elementary effect of the i-th parameter is defined as (Eq. (11)):

$$d_i(X) = \frac{y(x_1, ..., x_{i-1}, x_i + \Delta x_i, x_{i+1}, ..., x_k) - y(x)}{\Delta}$$

where $\Delta$ is the distance between two testing values of parameter $x_i$, and $y(X)$ is the objective function.

By setting different starting points $X$ from $\Omega$, we can obtain the distribution of elementary effects associated with the i-th input factor, denoted as $F_i$. Two sensitivity measures, the absolute mean ($\mu^*$) and the standard deviation ($\sigma$) of the $F_i$ can be calculated by Eqs. (12) and (13) (Campolongo et al., 2007):

$$\mu^*_i = \frac{1}{r} \sum_{j=1}^{r} |d_i(j)|$$

$$\sigma_i = \sqrt{\frac{1}{r-1} \sum_{j=1}^{r} \left( d_i(j) - \frac{1}{r} \sum_{j=1}^{r} d_i(j) \right)^2}$$

where $d_i(j)$ is the elementary effect for i-th input factor using the j-th starting point, $j = 1, 2, ..., r$; $r$ is the number of repeated parameter sampling design, which is also named trajectories of sample points in the parameter space $\Omega$. The number of $r$ is commonly set to be 9 levels $0, 0.125, ..., 0.875, 1$) and $r = 20$ trajectories are set for parameter samplings. Following Campolongo et al. (2007), the starting points for the trajectories are generated with Latin Hypercube Sampling (LHS), while the $\Delta = 0.5$ for $x_i < 0.5$ and $\Delta = -0.5$ for $x_i > 0.5$. The RMSD and PCC objective functions are applied. In general, 20*(6 + 1) = 140 simulations are performed for each rainfall event.

The $\mu^*$ estimates the overall effect of each parameter on the output, while the $\sigma$ estimates the higher order effects, such as nonlinearity and interactions between inputs, respectively.

### 3. Results and discussions

#### 3.1. Field data treatment and analysis

##### 3.1.1. Rainfall events selection

56 rainfall events have been identified during the study period of September 20, 2014 to April 27, 2015. Analysis of rainfall depth, mean intensity, event duration and antecedent dry days are performed for all the precipitation events in order to highlight their characteristics (Fig. 7).

According to Fig. 7(a) and (b), we can observe that most rainfall events within the study area of Eastern Paris, are considered low. In fact, more than 88% of rainfall events have a rain depth of less than 8 mm, and nearly 89% of rainfall events have a mean intensity of smaller than 3 mm/h. Additionally, Fig. 7(c) and (d) shows that event duration and antecedent dry days are a little more dispersed. However, most rainfall events observed are shorter than 7 h (87%), while 88% of the events are preceded by a previous rainfall event by less than 8 days.

As the distributed FullSWOF model is implemented on a $10^6$ pixel grid, the simulation is quite time-consuming. Therefore, we have to select several rainfall events which contain different characteristics in order to characterize the overall performance of the FullSWOF model within an urban context. Among the observed rainfall events, we selected 6 typical events for model application and performance evaluation, with the rainfall depths varying from 2 to 7.4 mm, the mean intensities differing from 0.8 to 2.9 mm/h, durations varying from 0.7 to 8 h, and antecedent dry days differing from 0.2 to 7.3 days. The summary of selected rainfall events is listed in Table 2.

#### 3.1.2. Total mass and PSD of TSS and dry stocks

The total mass of TSS for several rainfall events and the total weight of road dry stocks over the entire catchment are approximated based on stormwater samplings and road dust samplings, respectively (Fig. 8a). Meanwhile, the mass distributions of the washed off particles and the dry deposits for the entire catchment are compared in Fig. 8b.

Generally, the mass of washed-off particles collected in the sewer inlet is much lower than the estimated dry stocks, indicating that a large proportion of the deposited particles are not transferred into the sewer networks during the rainfall events. Moreover, the PSD of stormwater samples is quite different than that of surface dust samples. The TSS in surface runoffs contains most of fine particles (<50 $\mu$m), which represent more than 90% of total TSS load. While the small particles are only shown in a limited portion (<10%) of the surface dust samples. This phenomenon suggests that only the finest particles of road dry stocks could be transferred into

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**Table 1**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Definition</th>
<th>Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{0}$</td>
<td>kg/m³</td>
<td>Initial detachability of deposited sediment</td>
<td>1500–4500</td>
</tr>
<tr>
<td>$b$</td>
<td>–</td>
<td>Positive constant</td>
<td>0.8–2</td>
</tr>
<tr>
<td>$F$</td>
<td>–</td>
<td>Effective fraction of excess stream power</td>
<td>0.01–0.03</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>W/m²</td>
<td>Threshold stream power</td>
<td>0.15–0.35</td>
</tr>
<tr>
<td>$V_s$</td>
<td>m/s</td>
<td>Settling velocity</td>
<td>0.00001–0.001</td>
</tr>
<tr>
<td>$S$</td>
<td>kg/m²</td>
<td>Uniformly initial dry stock</td>
<td>0.0001–0.01</td>
</tr>
</tbody>
</table>
the sewer inlet during the average rainfall events.

For the modelling approach, since the TSS concentration is derived from turbidity observations and the turbidimeter (mini-probe OTT) can only measure fine particles (<2 mm), we focus on this part of sediments. By homogenizing the estimated weight of road dust (Fig. 8a, orange bars) for the entire catchment (2661 m²), the testing range of initial dry stocks is set to 0.1–10 g/m². The settling velocity is calculated with the particle size using Cheng (1997) equation. According to Fig. 8b (blue bars), the median diameter (d₅₀) of suspended solids in stormwater samples equals to 15 µm, while cumulative 10% and 90% points of diameter are d₁₀ = 5 µm and d₉₀ = 50 µm, respectively. Therefore, the tested range of settling velocity is calculated from the d₁₀ and d₉₀ of the Particle Size Distribution, equals to 0.00001–0.001 m/s.

3.1.3. Investigations of PAHs

In the framework of ANR-Trafipollu project, 13 types of PAHs (Fluorine, Phenanthrene, Benzos, etc.) have been found in 7 wet weather samples. The average percentages of investigated PAHs in particulate phases are presented in Fig. 9.

As shown in Fig. 9, most PAHs have more than 90% are associated with suspended particles, while the particulate fraction of Fluorone and Phenanthrene are slightly smaller, yet still remaining between 60% and 80%. This finding confirms our assumption of using TSS concentration as the indicator for urban stormwater quality modelling.
model performance. An optimized Manning coefficient value of 0.05 is calibrated for the event of Feb. 28th 2015 and validated for the other 5 examined rainfall events. As seen in Fig. 10, the performance of the quantitative simulation is quite satisfying. Compared to our previous work with the SWMM model (Rossman, 2010), the NSE value is improved from 0.7 to 0.9. Therefore, the use of such a physically-based and distributed model integrating the full shallow-water equations is more accurate than using only Mannings’ formula for the water flow simulation at the scale of a small road catchment.

3.3. Water quality simulations and parameter investigations

The Elementary-Effects (EE) method with 20 trajectories of 6 parameters is performed for the 2 rainfall events of Oct. 7th 2014 and Feb. 28th 2014. The cost is $20(6 + 1) = 140$ simulation runs for each event. The event of Oct. 7th 2014 has only one runoff peak while the other event contains several. Moreover, the durations of these two events are relatively short (only 2.2 and 40 min respectively), which require shorter simulation times compared to other precipitation events.

3.3.1. “Best-fitted” TSS simulations

The “best-fitted” TSS simulations with the 20 trajectories EE method are displayed in Fig. 11. Although the simulations are performed by using discrete parameter values with very limited calibration efforts, the results are quite promising for the road wash-off modelling. However, even though the performance of the model seems satisfying visibly, the NSE and RMSD criterion show poor outcomes, owing mainly to the significant deviation between the measured and simulated TSS concentrations. Since the objective of this study is to investigate the effects of parameter on TSS dynamics, the correlation coefficient (PCC) is a promising complement to assess model performance.

3.3.2. Sensitivity analysis of H-R parameters

The absolute mean ($\mu$) and the standard deviation ($\sigma$) of the distribution of elementary effects related with each parameter are obtained using EE method with 20 trajectories. The RMSD and PCC objective functions are applied to calculate the discrepancies between the measured and simulated TSS concentrations at the sewer inlet. The EE sensitivity measures are shown graphically by scatter plots in Fig. 12, which consist of the x- and y-axes the absolute mean ($\mu$) and the standard deviation ($\sigma$) of the TSS simulations with the 20 trajectories EE method are displayed in Fig. 11. Although the simulations are performed by using discrete parameter values with very limited calibration efforts, the results are quite promising for the road wash-off modelling. However, even though the performance of the model seems satisfying visibly, the NSE and RMSD criterion show poor outcomes, owing mainly to the significant deviation between the measured and simulated TSS concentrations. Since the objective of this study is to investigate the effects of parameter on TSS dynamics, the correlation coefficient (PCC) is a promising complement to assess model performance.

As illustrated in Fig. 12, the settling velocity ($V_s$) is the most sensitive parameter and the initial dry stock ($S$) is the second influential factor for either of the two presented rainfall event using different objective functions. While the others are relatively less sensitive ($b$, $a_{00}$, $\Omega_0$ and $F$). This result is caused by our assumption to simulate only one deposited layer with FullSWOF. Since all the initially available particles can be easily detached during the rainfall events, the sedimentation process and the initial dry stocks are the driving factors controlling the amount of particles on the surface for further wash-offs.

Concerning the detachment process, the parameters related to the raindrop-driven process ($b$, $a_{00}$) are much more important than that concerned with the flow-driven process ($\Omega_0$, $F$). Moreover, the $\Omega_0$ and $F$ seem to be insensitive to the TSS concentration at the sewer inlet. This finding suggests that the energy of simulated water flow rarely exceed the threshold of the stream power for initiating particle detachment. This implies that the wash-off process is predominately caused by raindrop impact for the investigated urban road catchment.

In addition to giving detailed information on the standard deviation ($\sigma$), the scatter plots also allow us to highlight possible...
interactions and nonlinear behaviours as well as identifying anomalies. According to Fig. 12, the parameter $V_s$ has the largest standard deviation in all conditions. This observation indicates that the interaction of $V_s$ with other parameters is more significant. Contrarily, the $\sigma$ of the parameters $b$ and $S$ are relatively less significant compared to their $\mu^2$. These two parameters are therefore more highlighted by their overall sensitivities. Moreover, it is shown in Fig. 12(d) that using the PCC objective function, the standard deviation ($\sigma$) of $\Omega_0$ becomes more important for the event of Feb 28, 2015. Since the event of Feb 28, 2015 is longer (2.2 h) than the other one (40 min) and contains several runoff and TSS concentration peaks after the first peak, the flow-driven process, which is linked to the parameters $\Omega_0$ and $F$, may be more responsible for the fluctuations of TSS concentration in the latest part of the rainfall event.

3.3.3. Continuous effects of the settling velocity ($V_s$) on TSS

Since the $V_s$ was confirmed to be the most influential parameter
on TSS dynamics in our study, a continuous TSS correlation analysis is performed in order to continuously investigate the effects of the settling velocity on the model performance for 5 rainfall events. The selected events contain several runoff peaks and TSS concentrations. Therefore, we fixed all other parameter values as the best-fitted simulations, while the $V_s$ is varied from its measured value (noted level 0, $d_{50} = 15 \mu m$, $V_s = 0.0001 m/s$) to a higher limit (noted level +1, $d_{90} = 50 \mu m$, $V_s = 0.001 m/s$) and a lower limit (noted level -1, $d_{10} = 5 \mu m$, $V_s = 0.00001 m/s$), separately. The results are displayed in Fig. 13.

As shown in Fig. 13, the effects of the settling velocity ($V_s$) on continuous TSS correlation are consistent for all studied rainfall events. For every tested value of $V_s$, the model is able to satisfactorily represent the dynamic trends until the first peak of TSS concentrations. However, it should be noted that the performance of the model is better with larger $V_s$ values in simulating the fluctuations after the first peak. This phenomenon can be explained by the assumption of single-class particles. In fact, the model does not consider the change in sediment-size distribution which occurs throughout the rainfall event. Due to the preferential deposition of the coarsest particles in regards to the grain-size distribution of the transported sediment, the representative settling velocity changed continuously during the rainfall event. Thus, we can argue that the subsequent peaks of TSS concentration are mainly caused by particles which are re-deposited after the occurrence of the first peak. In order to confirm this assumption, a detailed investigation of the road wash-off processes with different classes of sediment is suggested for the further studies.

### 3.4. What is the proper value of settling velocity for urban wash-off modelling?

As discussed above, the settling velocity ($V_s$) is the key parameter for road wash-off processes. However, in this case, it is revealed that the value of $V_s = 0.0001 m/s$, which is calculated from the measured median diameter of particles ($d_{50} = 15 \mu m$), is not suitable for reproducing the continuous dynamics of the TSS concentration for the road catchment. Therefore, we conclude that using the single-class sediments assumption, where the particle size equals to median diameter, is not capable of accurately reproducing the dynamics of TSS concentrations at the outlet of a road catchment, particularly for the later part of stormwater event. The application of the Particle Size Distribution with different classes of sediment could be suggested for more accurate simulations over the entire duration of a rainfall event. Nevertheless, since the single-class simplification could significantly reduce the computational time for such a physically-based and distributed model, this assumption could be used for specific objectives of water management. As shown in Fig. 12, the dynamics of the TSS concentration are generally well represented until the initial peaks, regardless of different values of settling velocity. We could therefore use the single class assumption in order to investigate water pollution limited to the first part of a rainfall event.

Besides, as observed by many researchers (Datry et al., 2003;
Julien, 2010; Kafi et al., 2008), the existence of a cohesive layer beneath the deposited urban dust layer might also be a meaningful explication for the present issue, with which coarser particles and flocculated fine particles can be detached only in the latest part of a storm event when the top layer has already been washed off. This assumption could also be investigated using the H-R and FullSWOF models in future studies.

4. Perspectives

In the previous sections, we introduced a novel approach to model urban stormwater quality with the physically-based FullSWOF and Hairsine-Rose (H-R) model. This new method has good potential for future studies in the following two aspects: (1) a helpful research approach for increasing understanding of urban wash-off mechanisms; (2) a useful tool for designing innovative stormwater management technologies.

Current urban wash-off models rely on empirical, catchment-scale functions (Sartor et al., 1974), that did not achieve significant advances for the last 40 years. Using the physically-based model coupled with high precision and fully-distributed data, researchers can have an insight view of the spatial and temporal heterogeneity of the dynamics of urban pollutants as well as the driving forces for wash-off mechanisms. This information is helpful for designing advanced experimental measurements and settings, in order to improve the underlying theories as well as the mathematical equations of urban wash-off processes. Nevertheless, since the present approach requires highly precise input data and the simulations are quite time-consuming, this method may be not suitable for large urban catchments as a research tool yet. The detailed studies of urban wash-off behaviours can nowadays only be focused on small-scale roads, buildings or greenlands.

On the other hand, accurate predictions of stormwater quality are very meaningful for planning and designing preventative measures. Benefitting from this physically-based approach, stormwater managers could have the knowledge of the spatial distribution of particles and particulate pollutants on the road surface. The stormwater pre-entrance technologies such as filter systems and storage tanks can be applied at-source for certain areas where more sediments trend to be settled. This type of source-control techniques are easier to implement comparing with other facilities at-the-end of catchment (e.g. wastewater treatment plants, storage basin, etc.) and can reduce the costs.

There is considerable scope for discussing the computational feasibility of applying this type of detailed physically-based model for large urban catchments. For example, how much spatial detail is needed to robustly represent wash-off processes for an urban catchment; and what kind of input information is necessary for successful water quality simulations. Undoubtedly, there is a need for systematic works on the suitability of, and methods for, such up-scaling. These investigations may be helpful for spreading this detailed urban wash-off modelling. Meanwhile, we are currently working on a multi-processor version of the FullSWOF model. This advancement may help further studies by reducing drastically the simulation time.
5. Conclusion

In the current study, the monitoring survey coupled with a rainfall approach by the physically-based FullSWOF model and the process-based Hairline-Rose model (H-R) is applied to a road catchment near Paris, in order to model the dynamics of urban wash-off. Centimetric resolution of topographic data, continuous measurements of rainfall intensities, water flows and turbidity measurements, as well as road dust and stormwater samplings are used in the model in order to obtain realistic input data. A global sensitivity analysis of 6 input factors is performed by using the Elementary-Effects (EE) method. This is the first time that such a research approach is applied and discussed in the context of urban wash-off modelling.

From on-site experimental measurements, the particle samplings show that the total mass and the Particle Size Distribution (PSD) in stormwater samples are quite different from that found in road dust samples, only the finest particles of the urban dry stocks can be transferred to the sewer inlet of the road catchment during a rainfall event. Meanwhile, it confirmed that most PAHs are found in the particulate phase and associated with suspended particles.

In our study, the H-R model coupled with FullSWOF software is for the first time applied to urban wash-off modelling. The simulation results indicate that the combined use of the models and high spatial- and temporal-resolution data provides a good representation of both water flow and water quality modelling.

Sensitivity analysis indicates that the settling velocity \(V_s\) and the initial dry stock \(S\) are the most sensitive parameters for either overall or second-order effects. The rainfall-driven detachment is revealed as the major force for detaching the sediment from the urban surface. However, the flow-driven detachment is more responsible for the fluctuations of TSS concentration in the latest part of the rainfall event.

The effects of settling velocity \(V_s\) on continuous PSD correlation are investigated throughout 5 different rainfall events. The value of \(V_s\), which is calculated from the single-class sediments assumption with \(d_50 = 15\, \mu m\), fell short of adequately reproducing the TSS dynamics, whereas coarser particles appear to be more adapted for modelling the TSS dynamics. Thus, a multi-class sediment perspective regarding the PSD is suggested for improving the model performance. Finally, the perspectives of using this new approach for increasing understanding of urban wash-off mechanisms, as well as for designing stormwater management technologies are discussed for future research and practical issues.

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