Water Research 102 (2016) 96–108

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

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

Yi Hong [a, *], Celine Bonhomme [a], Minh-Hoang Le [b], Ghassan Chebbo [a, c]

[a] University Paris-Est, Ecole des Ponts ParisTech, LEESU, 6-8 Avenue Blaise Pascal, 77455 Champs-sur-Marne Cedex 2, France
[b] Université Paris-Est, Ecole des Ponts ParisTech, Laboratoire Saint-Venant, 6 Quai Watier, 78400 Chatou, France
[c] Université Libanaise, Faculté de Génie, Campus Rafic Hariri, Hadat, Lebanon

ARTICLE INFO

Article history:
Received 3 February 2016
Received in revised form
5 May 2016
Accepted 12 June 2016
Available online 15 June 2016

Keywords:
Physically based and distributed model
Urban wash-off
Hairsine-Rose model
FullSWOF model
Sensitivity analysis

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 m^2). 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

---

* Corresponding author.
E-mail address: yi.hong@leesu.enpc.fr (Y. Hong).

http://dx.doi.org/10.1016/j.watres.2016.06.027
0043-1354/© 2016 Elsevier Ltd. All rights reserved.

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 raindrops 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 m^2, 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 Particles 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) Trafipollu 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 m^2) are used to calculate the total mass of road dust on the catchment surface (2661 m^2). Likewise, the total mass of loaded TSS during a rainfall event can be calculated by multiplying the