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Investigation of the wash-off process using an innovative portable rainfall simulator allowing continuous monitoring of flow and turbidity at the urban surface outlet

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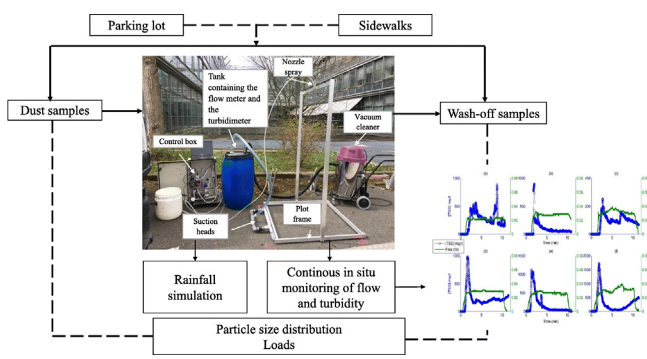
HIGHLIGHTS

- An innovative portable rainfall simulator is developed and calibrated.
- Simulated flow and turbidity dynamics are continuously monitored *in situ*.
- Particles (<100 μm) are the most susceptible for mobilization by the runoff.
- Smoother surfaces generate higher loads of TSS in runoff.

GRAPHICAL ABSTRACT



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ABSTRACT

Development of appropriate models, based on an in-depth understanding of the wash-off process, is essential to accurately estimating pollutant loads transported by stormwater, thereby minimizing environmental contamination. To this end, we developed an innovative rainfall simulator, which simulated an intense rainfall (120 mm/h) and permitted the acquisition of runoff samples as well as the *in situ* monitoring of continuous flow and turbidity dynamics. Relationships between deposited sediments and total suspended solids in simulated runoff were thus investigated on two different types of surfaces within the Paris region in terms of loads and particle size distribution. Results demonstrate the occurrence of first flush phenomenon on the sidewalks even under constant flow. Results also show that the highest fraction conveyed by runoff consisted of fine (<16 μm) and medium-sized (<100 μm) particles, whose detachment was more favorable from smooth surfaces than from rougher ones. In terms of stormwater quality modelling, results suggest that the integration of a wash-off fraction based on both particle size and rainfall intensity could be an entrance for a better prediction of stormwater pollution.

1. Introduction

Modification of land surface due to urban expansion has led to a significant increase in impervious surfaces (Wilson and Weng, 2010). This has been accompanied by a rise in the volume of urban stormwater runoff (Chen et al., 2016) and pollutant loads. Pollutant wash-off from

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impervious surfaces in urban catchments, mainly roads and parking lots, is a major contributor to stormwater runoff contamination (Motelay-Massei et al., 2006; Revitt et al., 2014). During a rainfall event, pollutants deposited on the surface during the dry weather period will be mobilized in different forms and migrate into the sewer system. Pollutants transported within the particulate matter are recognized as the main source of contamination as toxic elements such as trace metals and polycyclic aromatic hydrocarbons as well as organic matter are adsorbed on their surface and scattered over the particles in several size fractions (Kim and Sansalone, 2008; Sansalone et al., 1998; Zhao and Li, 2013). The most common indicator for particulate matter is the total suspended solids (TSS) (Rossi et al., 2013). The direct discharge of TSS into the receiving water bodies will pose a severe environmental risk if left untreated. The evaluation of such risk is primarily based on the understanding of build-up and wash-off processes (Deletic and Orr, 2005; Egodawatta et al., 2013; Vaze and Chiew, 2002), and in-depth investigation of relationships between sediment deposits and fractions transported by wash-off (Eckley and Branfireun, 2009; Zhao and Li, 2013). Furumai et al. (2002) showed that surface wash-off is highly dependent on the particle sizes that are present prior to a storm event, noting that more than half of the particulate load in runoff samples are associated with particles < 20 μm. In a recent study, Hong et al. (2016b) demonstrated that most fine particles (<15 μm) are transported at the beginning of a rainfall event, while a number of coarser particles are transported later if the rainfall intensity is high enough, or if there is sufficient energy in the flow. These findings confirm that fine and coarse particles exhibit distinct transport behavior, revealing the need to not only compare particulate matter in terms of load, but also size distribution (Kim and Sansalone, 2008; Wijesiri et al., 2015; Zhao et al., 2010). Therefore, it is essential to incorporate this knowledge into stormwater quality models in order to enhance and elucidate the current description of the complex processes governing the generation and transport of pollutants. Obtaining new knowledge on these processes and their controlling factors requires an in-depth investigation in order to acquire the necessary data.

Several sampling techniques have been used to collect build-up and wash-off samples. Build-up samples are usually obtained either by spraying water on the surface and then collecting the effluent using a vacuum cleaner (Deletic and Orr, 2005) or by brushing the surface and dry vacuuming (Eckley and Branfireun, 2009; Vaze and Chiew, 2002). Both methods have high sampling efficiency and allow the collection of the fine particles that are dislodged under the pressure of water spray or the action of the brush. However, it should be noted that an accurate estimate of the available pollutant load on the surface alone is not sufficient in determining the level of contamination in the runoff. In fact, several studies have shown that the amount transported by stormwater runoff is minimal compared to the amount of stock present on the surface (Hong et al., 2016a; Pitt et al., 2005), suggesting that wash-off sampling is a necessary complement to dust sampling in evaluating stormwater contamination.

Stormwater samples obtained from natural rainfall are usually collected at the catchment outlet, which is equipped with automatic samplers (Al Ali et al., 2016; Goonetilleke et al., 2005; Liu et al., 2013). Using these types of samples in order to understand and elucidate erosion and wash-off mechanisms is difficult given the high variability of rainfall characteristics and the random nature of rainfall events. To overcome these challenges, researchers resorted to artificial rainfall, where rainfall is generated under controlled conditions using rainfall simulators (Egodawatta et al., 2007; Herngren et al., 2005; Zhao and Li, 2013). Artificial rainfall conditions are favorable, since they allow for the simulation of different rainfall scenarios. This will help identify key explanatory factors that can be implemented in the mathematical replication of the wash-off process. By simulating rainfalls of different intensities and durations to investigate the wash-off of pollutants from urban road surfaces, Zhao and Li (2013) concluded that the wash-off fraction is proportional to both factors, as intense rainfall mobilized the highest fraction of loads. Based on similar results, Egodawatta et al. (2007) developed a new wash-off model by modifying the original exponential wash-off equation proposed by Sartor et al. (1974) and introducing a capacity factor that depends on rainfall intensity. These studies highlight the interest of using rainfall simulators to study wash-off; however, the results were analyzed only in terms of loads and their corresponding particle size distribution. Until now, no study has allowed for *in situ* analysis of the instantaneous hydrographs and pollutographs generated by the simulated runoff.

Another constraint of previous studies is the fact that rainfall simulators usually require more than one person to install and operate, adding time to the sampling process and making it impossible to perform several experiments on the same day at different locations. In addition, some simulators might not be used on real sites outside of the laboratory because of their sophisticated design. Therefore, the development of a portable field rainfall simulator seems adequate in addressing this issue. In fact, a number of studies have investigated wash-off using portable field rainfall simulators in natural catchments (Battany and Grismer, 2000).

In this paper, an innovative device consisting of a lightweight mobile rainfall simulator, equipped with a measuring system that allows for the continuous *in situ* monitoring of flow and turbidity, and thus the investigation of instantaneous hydrograph and pollutograph, was designed to study the transport dynamics of TSS from paved zones of two distinct surfaces. Dust and water samples were collected and compared in terms of loads and particle size distribution on both surfaces. Results are interpreted with the view of understanding the physical process of pollutant production and enhancing the current modelling approaches of stormwater wash-off.

2. Materials and methods

2.1. Study area

The research sites are located in two different districts situated in the eastern part of the Paris region. They were chosen to represent different surface types. The first site consisted of the sidewalks located at proximity of the highly trafficked (up to ~30,000 vehicles per day) boulevard "Alsace Lorraine" in the residential district of "Le Perreux sur Marne" in the department of "Val de Marne". The surrounding area includes residential houses and small commercial shops. The sidewalks are characterized by a smooth surface.

The second research site was a parking lot in the University of "Ecole des Ponts Paristech". The university is located in the district of "Champs sur Marne" within the department of "Seine et Marne". The parking surface is made of coarse asphalt and is subjected to low traffic density.

The surfaces at both locations are presented in Fig. 1.

2.2. Rainfall simulator, measuring system and experimental data

2.2.1. Design and conception

A specially designed portable field device consisting of a rainfall simulator and a measuring system that allows for continuous monitoring of flow and turbidity was used in this study. The device was designed to homogeneously spray an elementary area of 1 m^2, with a one-year return period rainfall having a raindrop size distribution similar to the natural regional rainfall. Lightweight materials were used in the construction of the device so that it could be easily operated by one person and to reduce implementation time to less than an hour.

The simulator consisted of two aluminum frames: the first was a U-shape, where the nozzle spray and hollow parallelepipedic legs were attached; the other was a square plot frame (1 m × 1 m) that delineated the plot boundary. The two frames were assembled by fitting the legs of the U-shaped frame into two parallelepipedic tubes fixed between two parallel outside borders of the plot frame, with an internal length equal to the external length of the legs of the U- shaped frame.