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Re-thinking classical mechanistic model for pollutant build-up on urban impervious surfaces

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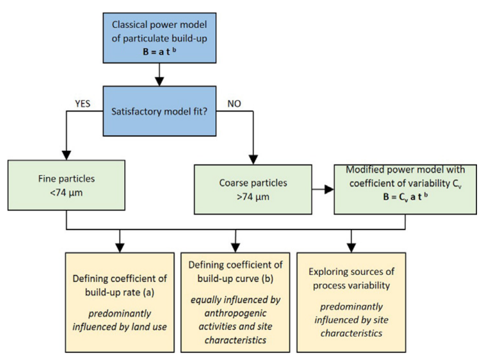
HIGHLIGHTS

- Classical power model satisfactorily replicates build-up of fine particles.
- A new 'coefficient of variability' better replicates build-up of coarser particles.
- Coefficients of build-up rate and build-up curve were defined.
- Site characteristics largely influence the variability due to particle behaviour.

GRAPHICAL ABSTRACT



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ABSTRACT

Accurate modelling of particulates build-up process is essential for designing effective stormwater management strategies. However, current modelling practice relies on the classical 'power model' which has limitations in accounting for the variability in the build-up process. This research study investigated the relationships between influential factors of the build-up process and coefficients in the power model. The outcomes showed that the coefficient, which determines the build-up rate, is predominantly influenced by land use factors (pervious area, road area, commercial area and residential area), such that land use factors exerted 23 times more influence than the site characteristics (distance to pervious area and road surface texture depth). The coefficient, which determines how quickly build-up reaches equilibrium, was found to be equally influenced by anthropogenic activities (sweeping frequency and traffic volume) and site characteristics. Further, site characteristics were found to play a major role in generating build-up process variability with three times more influence than that of anthropogenic activities. It was found that the power model satisfactorily replicates the build-up of particles <74 µm. For the build-up of particles >74 µm, a new coefficient, namely, 'coefficient of variability' was introduced in order to improve the prediction performance (up to 17% compared to original power model). The study outcomes provide a deeper understanding into particulates build-up modelling, and can contribute to the formulation of effective stormwater treatment strategies.

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1. Introduction

Due to increasing urbanization, stormwater runoff pollution has become the primary diffuse pollutant source in urban catchments (Taebi and Droste, 2004). The pollutants in stormwater runoff originate from deposition on urban impervious surfaces over the antecedent dry period between rainfall events (Zhao et al., 2010). Particulate solids are recognized as the primary pollutant found on impervious surfaces and as the carrier of significant amounts of other pollutants such as heavy metals and hydrocarbons (Gunawardana et al., 2012a; Jayarathne et al., 2018; Song et al., 2015). Mitigating particulate pollutants accumulated on urban impervious surfaces play an important role in safeguarding urban receiving water environments (Yu et al., 2016; Liu et al., 2018). Therefore, designing of effective stormwater pollution mitigation strategies needs informed decision making based on accurate particulates build-up modelling (Li et al., 2018).

Sartor and Boyd (1972) noted that particulate pollutants accumulation on road surfaces can be replicated mathematically using a decreasing rate increasing function and also identified several hypothetical patterns of pollutant build-up on road surfaces. Based on these patterns, four empirical build-up models, namely, asymptotic model (Roesner, 1982) linear model (Soonthornnonda and Christensen, 2008), exponential model (Sartor et al., 1974; Charbeneau and Barrett, 1998) and power model (Ball et al., 1998) have been commonly applied to mathematically replicate the pollutant build-up process.

Zhang and Zhou (2005) used the asymptotic model to simulate runoff pollutant concentration in a city in southern Jiangsu Province, China, and achieved satisfactory outcomes. Soonthornnonda and Christensen (2008) predicted the pollutant concentration in runoff for Milwaukee area based on the linear model, and it was found that the model performs well for BOD_5 (5 Day Biochemical Oxygen Demand), TSS (Total Suspended Solid) and TP (Total Phosphorus). However, Ball et al. (1998) found that the power model is the most suitable for simulating the pollutant build-up process, not only for particulates, but also particle-bound pollutants such as Zn, Pb and Cu. In a later study, Egodawatta (2007) also confirmed the suitability of the power model in replicating the build-up process.

However, numerous studies, on the other hand, have noted that intrinsic process variability is created due to the fact that coarser particles exhibit behaviours that are distinct from finer particles during build-up (Kayhanian et al., 2008; Wijesiri et al., 2015a). The particle behaviour implies that all movement of particles are impacted by natural conditions and anthropogenic activities that take place over the course of the build-up period. Inaccurate replication of particle behaviour and process variability reduces the reliability of the modelling outcomes (Wijesiri et al., 2016).

The aim of this study was to develop an in-depth understanding of how natural and anthropogenic factors influence the build-up process variability, and thereby improve the accuracy of particulates build-up modelling. In order to accomplish this aim, a systemic study approach was adopted. The study consisted of the following primary steps: (1) mathematical modelling of particulates build-up for different particle size ranges using the power model; (2) for the particle size fractions which fitted well to the model, investigating the relationship between influential factors in the build-up process and the coefficients of the power model; and (3) refining the power model for the particle size fractions where the model prediction performance was not satisfactory, by incorporating process variability. The study discussed in this paper not only focused on modifying the classical mechanistic model for pollutant build-up, but also investigated the sources of build-up process variability. The study outcomes are expected to contribute to improving the current practice in stormwater quality modelling, and in turn, the design of effective pollution mitigation strategies to protect urban receiving water environments.

2. Materials and methods

2.1. Study area

The investigations were conducted at five sites in Hebi City, Henan Province, China. Hebi is located in north of China, hosts 1.6 million people, and has a sub-humid climate with wet summers and dry winters with an annual rainfall range of 350–970 mm and average annual temperature of about 14 °C. As shown in Fig. 1, all five study sites (R1, R2, R3, R4 and F1) were surrounded by grassed area, and consisted of different land uses, site characteristics and anthropogenic activities. Further details of the characteristics of the study sites are provided in Table S1 in the Supplementary Information.

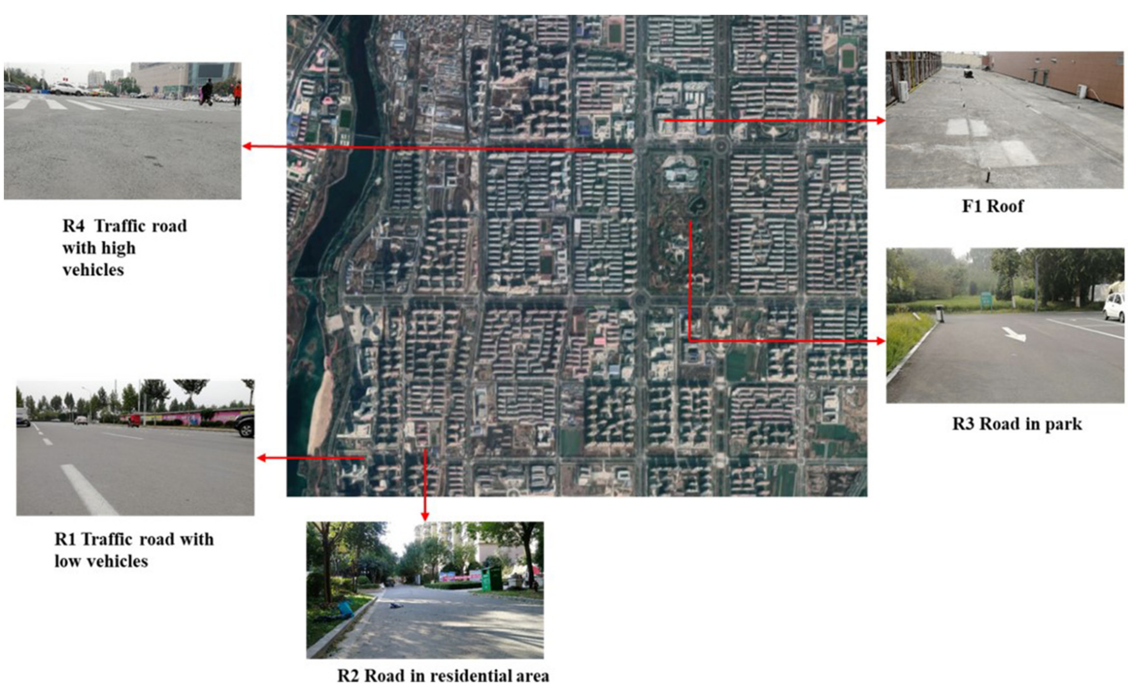

Fig. 1. Locations of study sites.