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Process variability of pollutant build-up on urban road surfaces

Buddhi Wijesiri, Prasanna Egodawatta, James McGree, Ashantha Goonetilleke *

Science and Engineering Faculty, Queensland University of Technology, GPO Box 2434, Brisbane, 4001 Queensland, Australia

HIGHLIGHTS

- Study has identified the intrinsic variability in pollutant build-up.
- Variability in particle behavior primarily induces build-up process variability.
- Particles <150 μm and >150 μm exhibit distinct behaviors during build-up.
- Behavioral variability of particles <150 μm mostly influences process variability.

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ABSTRACT

Knowledge of the pollutant build-up process is a key requirement for developing stormwater pollution mitigation strategies. In this context, process variability is a concept which needs to be understood in-depth. Analysis of particulate build-up on three road surfaces in an urban catchment confirmed that particles <150 μm and >150 μm have characteristically different build-up patterns, and these patterns are consistent over different field conditions. Three theoretical build-up patterns were developed based on the size-fractionated particulate build-up patterns, and these patterns explain the variability in particle behavior and the variation in particle-bound pollutant load and composition over the antecedent dry period. Behavioral variability of particles <150 μm was found to exert the most significant influence on the build-up process variability. As characterization of process variability is particularly important in stormwater quality modeling, it is recommended that the influence of behavioral variability of particles <150 μm on pollutant build-up should be specifically addressed. This would eliminate model deficiencies in the replication of the build-up process and facilitate the accounting of the inherent process uncertainty, and thereby enhance the water quality predictions.

1. Introduction

Pollutant build-up is the process by which pollutants of natural and anthropogenic origin are accumulated on urban impervious surfaces such as roads, driveways and roofs over a period of dry weather. These pollutants are found to exhibit temporal variations in pollutant load (total amount of pollutants) and composition (mixture of fractional amounts of different pollutants) during build-up (Deletic and Orr, 2005; Viklander, 1998). Consequently, process variability needs to be incorporated into the build-up process in terms of variations in pollutant load and composition. Researchers such as Dempsey et al. (1993) and Zafra et al. (2011) found that most road deposited pollutants (e.g. heavy metals) are primarily associated with particles. Consequently, particulate solids are recognized as a primary pollutant found on urban road surfaces and the carrier of significant amounts of other pollutants (Gunawardana et al., 2012). Pollutant affinity for particles therefore suggests that variations in pollutant load and composition are likely to be influenced by particle behavior. In this paper, the term "particle behavior" refers to the physical movement of particles while undergoing deposition and re-distribution that result from natural and anthropogenic activities (e.g. wind, traffic, periodic street sweeping). In fact, the behavior of particles also exhibits significant variability during build-up (Patra et al., 2008; Sabin et al., 2006). Therefore, variability in particle behavior is suggested to be the primary source that induces process variability.

Numerous studies have postulated that coarse particles exhibit behavior distinct from that of finer particles during build-up. For example, coarse particles preferentially deposit on ground surfaces in a relatively short period of time, while fine particles can remain suspended over a longer period in the atmosphere due to slower settling velocities (Kayhanian et al., 2008; Roger et al., 1998). Consequently, the behavior of fine and coarse particles would also be different during re-distributional processes (e.g. re-suspension, aggregation, fragmentation). As such, fine particles in the atmosphere can potentially aggregate due to attractive inter-particle forces, while accumulated coarse

* Corresponding author.
E-mail addresses: b.mahappukankanamalage@qut.edu.au (B. Wijesiri), p.egodawatta@qut.edu.au (P. Egodawatta), james.mcgree@qut.edu.au (J. McGree), a.goonetilleke@qut.edu.au (A. Goonetilleke).

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particles are subject to re-suspension and fragmentation by activities such as vehicular traffic. This in effect suggests that particle size influences particle behavior. On the other hand, as a result of particle aggregation and fragmentation, particle size is found to change during build-up (Vaze and Chiew, 2002). Therefore, it is evident that the variability in particle behavior is potentially generated from the change in particle size, signifying the influence of particle size on process variability.

Sartor and Boyd (1972) identified several hypothetical patterns of pollutant build-up on road surfaces. They contended that build-up would gradually asymptote towards a maximum value over the period between two removal events such as rainfall and/or street sweeping. Ball et al. (1998) and Egodawatta et al. (2013) observed similar behavior, and their experimental data were found to be in agreement with a pattern that increases at a decreasing rate. However, this build-up pattern only depicts how build-up varies over time. Noticeably, the hypothetical and observed patterns of build-up presented in literature do not provide sufficient information about variations in the composition of pollutant load and variability in particle behavior. Additionally, process variability particularly during re-distribution is not clearly explained. The study discussed in this paper identifies the variations in pollutant load and composition and the variability in the behavior of particles of different size ranges, in order to explain the pollutant build-up process variability. As particulate solids carrying a range of pollutants contribute to the deterioration of urban stormwater quality, the new knowledge on pollutant build-up presented in this paper is expected to assist in enhancing stormwater pollution mitigation strategies.

2. Materials and methods

2.1. Data, data sources and study sites

Experimental data on total particulate build-up over different antecedent dry periods and corresponding particle size distributions on three road surfaces (Gumbeel Court, Lauder Court and Piccadilly Place) were obtained from the research study undertaken by Egodawatta (2007). Total particulate build-up data were available for dry periods of 1, 2, 3, 7, 14 and 23 days for Gumbeel Court and Lauder Court sites, and for dry periods of 1, 2, 7, 14 and 21 days for Piccadilly Place site. The particle size distributions (%) spanned from 1 μm to 900 μm.

The build-up sampling was conducted on small road surface plots (2.0×1.5 m) using a portable wet vacuum system. Total particulate build-up was determined using gravimetric methods. Particle size distribution was analyzed using the Malvern Mastersizer S instrument, which uses a laser diffraction technique (Malvern Instrument Ltd., 1997). Detailed information on build-up sampling and analysis is provided in Herngren et al. (2006).

The study sites were located within a residential catchment in Highland Park, Gold Coast, Australia. The locations of the study sites are shown in Fig. S1 in the Supplementary information. Each road surface is distinguished by differences in urban form and variations in traffic volume and road surface conditions. The details of urban form (type of housing, number of households and population density) and road surface condition (slope and texture depth) that correspond to each study site are given in Table 1.

2.2. Preliminary data analysis and mathematical replication of particulate build-up

An analysis of the temporal variation of particulate build-up on each road surface was conducted to investigate the differences in the shape of the particle build-up patterns for different size ranges. Subsequently, build-up patterns of size-fractionated particles were mathematically replicated, such that non-linear regression relationships between particulate build-up and antecedent dry days could be developed. These relationships were based on the unique shape of each pattern identified from the preliminary analysis. Mathematical replication was required in order to generate more generalized illustrations of the build-up patterns of individual particle size fractions, and thereby to ascertain the consistency of the build-up patterns over different field conditions (e.g. vehicular traffic volume, road surface condition).

Regression parameters for non-linear regression relationships were estimated with the aid of the in-built MATLAB function *nlinfit*. The function *nlinfit* estimates parameters using 'iterative least squares estimation', with specified initial values (MathWorks, 2013). This enabled the prediction of fractional build-up (build-up of particle size fractions) over the antecedent dry period. The variations in predicted fractional build-up are presented as the generalized illustrations of build-up patterns (described in Section 3.3).

2.3. Development of theoretical build-up patterns

After the verification of the consistency in build-up patterns from generalized illustrations, they could be logically arranged to explain the variability of pollutant build-up that occurs under all potential conditions in the field. Accordingly, the theoretical patterns that depict the temporal variation in total particulate build-up under the influence of different field conditions were developed based on the generalized illustrations of fractional build-up patterns. In fact, the characteristic shape of each fractional build-up pattern in generalized illustrations was considered when developing the theoretical build-up patterns. This means that each theoretical pattern was a different combination of fractional build-up patterns.

3. Results and discussion

3.1. Role of particle size on particle behavior

In the initial analysis, total particulate build-up corresponding to different antecedent dry days was distributed over nineteen particle size ranges spanning from 1 μm to 900 μm. The size-fractionated particulate build-up was plotted against the antecedent dry days for all three study sites as shown in Fig. 1. Significant differences in the shape of the build-up patterns for the individual particle fractions were noted.

Analysis of the size-fractionated build-up data sets corresponding to each study site confirmed that particle size fractions <150 μm and >150 μm have characteristically different patterns of build-up. As shown in Fig. 1, the fraction <150 μm was found to decrease over the antecedent dry period, while the fraction >150 μm gradually increased. This implies that particles <150 μm are more susceptible to be re-distributed, while particles >150 μm continuously undergo deposition.

Table 1
Characteristics of study sites.
Adapted from Egodawatta (2007).

Study site	Urban form			Road surface condition	
	Housing type	Number of households	Population density	Slope (%)	Texture depth (mm)
Gumbeel Court	Duplex housing	25	High	7.2	0.92
Lauder Court	Single detached housing	12	Low	10	0.66
Piccadilly Place	Single detached housing	41	High	10.8	0.83