Environmental Pollution 212 (2016) 48–56

Contents lists available at ScienceDirect

Environmental Pollution

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

Invited paper

Assessing uncertainty in pollutant build-up and wash-off processes[☆]

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ARTICLE INFO

Article history:
Received 21 August 2015
Received in revised form
15 January 2016
Accepted 19 January 2016
Available online xxx

Keywords:
Particle size
Process uncertainty
Pollutant build-up
Pollutant wash-off
Stormwater pollutant processes
Stormwater quality

ABSTRACT

Assessing build-up and wash-off process uncertainty is important for accurate interpretation of model outcomes to facilitate informed decision making for developing effective stormwater pollution mitigation strategies. Uncertainty inherent to pollutant build-up and wash-off processes influences the variations in pollutant loads entrained in stormwater runoff from urban catchments. However, build-up and wash-off predictions from stormwater quality models do not adequately represent such variations due to poor characterisation of the variability of these processes in mathematical models. The changes to the mathematical form of current models with the incorporation of process variability, facilitates accounting for process uncertainty without significantly affecting the model prediction performance. Moreover, the investigation of uncertainty propagation from build-up to wash-off confirmed that uncertainty in build-up process significantly influences wash-off process uncertainty. Specifically, the behaviour of particles <150 μm during build-up primarily influences uncertainty propagation, resulting in appreciable variations in the pollutant load and composition during a wash-off event.

1. Introduction

An in-depth understanding of the processes, which stormwater pollutants undergo, is vital for effective pollution mitigation (Barbosa et al., 2012; Mahbub et al., 2010; Wang et al., 2011). Stormwater pollutants undergo two fundamental processes, namely, pollutant build-up and wash-off. During dry weather conditions, pollutants build-up on impervious surfaces such as roads under the influence of a range of natural and anthropogenic activities (e.g. wind, vehicular traffic). The accumulated pollutants are subsequently washed-off during storm events (Chiew et al., 1997; Duncan, 1995).

Pollutant build-up and wash-off are highly dynamic processes, where variability is inherent due to continuous changes to the pollutant load and composition over the antecedent dry period (during build-up) and over the duration of a storm event (during wash-off). Process variability primarily stems from the behaviour of different sized particles while undergoing build-up and wash-off (Hvitved-Jacobsen et al., 2010; Sabin et al., 2006; Viklander, 1998). Wijesiri et al. (2015a, b) reported that the variations in particle-bound pollutant load and composition during build-up and wash-off is primarily influenced by the behaviour of particles <150 μm and >150 μm. Moreover, past studies have also emphasized the significance of these two particle size fractions in relation to build-up and wash-off of pollutants (Goonetilleke et al., 2009; Herngren et al., 2006; Li et al., 2015).

Process variability introduces inherent uncertainty to build-up and wash-off processes (Wijesiri et al., 2015a, 2015b; Zoppou, 2001). The process uncertainty, which is often referred to as aleatory uncertainty, is one of the two types of uncertainties associated with stormwater quality modelling outcomes. The other type of uncertainty is the uncertainty associated with stormwater quality modelling itself, which arises from the simplification of processes being modelled due to lack of in-depth knowledge of these processes. The uncertainty due to incomplete knowledge is categorised as epistemic uncertainty (Helton and Burmaster, 1996; Stewart, 2000). These uncertainties play an important role in the context of stormwater pollution mitigation (Loucks et al., 2005).

The primary focus in stormwater pollution mitigation is to safeguard urban receiving water quality, and thereby to reduce the potential risk to human and ecosystem health. In this regard, the effectiveness of pollution mitigation strategies which depends on scientifically robust management and planning decisions is the key to minimising potential health risks. However, decision making in relation to stormwater pollution mitigation is commonly

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[☆] This paper has been recommended for acceptance by Baoshan Xing.

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http://dx.doi.org/10.1016/j.envpol.2016.01.051
0269-7491/

undertaken using the outcomes generated by stormwater quality models without a complete understanding of the uncertainty associated with the model outcomes. Consequently, there exists the potential risk of failure of pollution mitigation strategies to improve stormwater quality (Loucks et al., 2005; WWAP, 2012; Xu and Tung, 2008). As such, it is important to assess the associated uncertainty in order to strengthen the interpretation of model outcomes for informed decision making (Haddad et al., 2013; Lee et al., 2012; Sun et al., 2012; Zoppou, 2001). In this context, epistemic uncertainty can be reduced either by enhancing the state of knowledge or by accounting for this uncertainty based on an uncertainty analysis. However, aleatoric process uncertainty is irreducible due to its inherent nature (Loucks et al., 2005; Ross et al., 2009; Vezzaro and Mikkelsen, 2012). Consequently, specifically accounting for process uncertainty is the most feasible approach.

Typical uncertainty assessment techniques used in stormwater quality modelling generally account for uncertainty generated from sources such as model structure, model parameters and data (Dotto et al., 2012). For example, the classical Bayesian approach based on Markov Chain Monte Carlo method and the Metropolis–Hastings Sampler (Beven, 2009; Doherty, 2003), Generalized Likelihood Uncertainty Estimation (Beven and Binley, 1992), Multi-algorithm Genetically Adaptive Multi-objective method (Vrugt and Robinson, 2007), and Shuffled Complex Evolution Metropolis Algorithm (Vrugt et al., 2003) can be identified as widely used techniques. However, some of the uncertainty sources are not taken into the consideration in these approaches (Rauch and Harremoës, 1999). Additionally, Dotto et al. (2012) has pointed out that most approaches have limited application due to the use of different subjective criteria such as user defined likelihood measures and the influence of prior knowledge in Bayesian techniques (Freni and Mannina, 2010; Freni et al., 2009; Mannina and Viviani, 2010). In effect, these limitations could significantly impact on management and planning decisions for stormwater pollution mitigation. In the context of assessing process uncertainty, the limitations in accounting for uncertainty can be attributed to poor characterisation of the source of uncertainty (process variability) in stormwater quality modelling.

The research study discussed in this paper was undertaken to develop methodology to quantitatively assess the uncertainty inherent to pollutant build-up and wash-off from typical urban road surfaces. The study was based on the hypothesis that when build-up and wash-off models are incorporated with the relevant process variability, uncertainty can be quantified as an integral part of the uncertainty associated with the model predictions. The incorporation of process variability into build-up and wash-off models was based on mathematical formulations of the temporal variations of particles <150 μm and >150 μm during build-up and wash-off (Wijesiri et al., 2015c). The outcomes of the uncertainty assessment presented in this paper will help to guide the accounting of process uncertainty in relation to commonly used stormwater quality models. This will be based on an in-depth understanding of the characteristics of process variability in combination with an innovative approach to accurately incorporate these characteristics into models. This innovative approach is expected to contribute to improved decision making for designing effective stormwater pollution mitigation strategies.

2. Materials and methods

2.1. Study sites

Three build-up and wash-off sampling sites located on urban residential roads in Gold Coast, Australia, namely, Gumbeel Court, Lauder Court and Piccadilly Place were selected for detailed investigations. The locations of road sites are shown in Fig. S1 in the Supplementary Information. All three road sites are characterised by typical residential urban form and different traffic volumes. Gumbeel Court serves a housing estate consisting of 25 duplex type households. The surrounding urban form at Lauder Court consists of 12 single detached households. Piccadilly Place serves 41 single detached households. The asphalt paved road surfaces at each site were in good condition with surface texture depth and longitudinal slope of 0.92 mm and 7.2% at Gumbeel Court, 0.66 mm and 10% at Lauder Court, and 0.83 mm and 10.8% at Piccadilly Place, respectively.

2.2. Build-up and wash-off sampling and laboratory analysis

A portable wet vacuum system (Delonghi Aqualand Model), which is incorporated with a water filtration unit, was used to collect particulate build-up samples. The sampling efficiency of the vacuum system was found to be 97%. For the wash-off experiments, a rainfall simulator was used as it was necessary to collect samples over storm events with different characteristics. The simulation performance of the rainfall simulator for storm events with specific intensities and durations was verified prior to the field experiments. Egodawatta (2007) and Herngren (2005) provide detailed information about the performance verification of the vacuum system and the rainfall simulator and procedures for pollutant build-up and wash-off sampling.

Particulate build-up and wash-off samples were collected for different antecedent dry periods and for simulated storm events with different intensities, respectively. The antecedent dry periods considered for Gumbeel Court and Lauder Court were 1, 2, 3, 7, 14 and 23 days, while at Piccadilly Place, build-up sampling was undertaken for antecedent dry periods of 1, 2, 7, 14 and 21 days. The simulated storm events at Gumbeel Court and Piccadilly Place were 20, 40, 65, 86, 115 and 133 mm/h intensity, while intensities of 40, 65, 86, 115 and 133 mm/h were simulated at Lauder Court. The storm event durations that corresponded to intensities of 20, 40, 65 and 86 mm/h were 40, 35, 30, 25 min, respectively, and the storm events with intensities of 115 and 133 mm/h were simulated over a duration of 20 min. The selected storm event durations were threshold durations beyond which pollutant wash-off is insignificant. This is because the impact of raindrop kinetic energy on particle mobilisation decreases with time due to the development of sheet flow. Further details relating to the mobilisation of particles from urban road surfaces during a storm event can be found in Vaze and Chiew (2000) and Egodawatta (2007). Additionally, prior to undertaking wash-off experiments, samples of the particulate build-up available on each road surface were also collected. Particulate solids load in the build-up and wash-off samples were determined using test methods 2540C (dissolved solids) and 2540D (suspended solids) (APHA, 2012). A Malvern Mastersizer S analyser was used to determine the particle size distribution of build-up and wash-off samples. A particle size range of 0.05–900 μm can be analysed using this instrument. The use of quality audit standards QAS3002 and QAS3001-B enabled verification of the performance of the instrument (Malvern Instrument Ltd, 1997).

2.3. Data analysis

Data analysis was undertaken in two phases: prediction of particulate build-up and wash-off and quantification of uncertainty associated with these predictions; and comparison of uncertainty between primary and revised mathematical models of build-up and wash-off processes. The primary models are common