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Incorporating process variability into stormwater quality modelling

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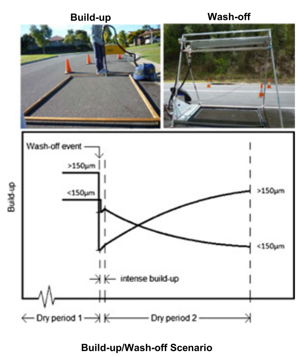
HIGHLIGHTS

- Theoretical scenarios for pollutant build-up and wash-off variability are proposed.
- The scenarios combine build-up and wash-off processes on a continuous time-line.
- Process variability characteristics under different field conditions identified
- The scenarios explain the variability in pollutant build-up and wash-off processes.
- Presents approach to account process variability in stormwater quality modelling

GRAPHICAL ABSTRACT



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ABSTRACT

Process variability in pollutant build-up and wash-off generates inherent uncertainty that affects the outcomes of stormwater quality models. Poor characterisation of process variability constrains the accurate accounting of the uncertainty associated with pollutant processes. This acts as a significant limitation to effective decision making in relation to stormwater pollution mitigation. The study undertaken developed three theoretical scenarios based on research findings that variations in particle size fractions < 150 μm and > 150 μm during pollutant build-up and wash-off primarily determine the variability associated with these processes. These scenarios, which combine pollutant build-up and wash-off processes that takes place on a continuous timeline, are able to explain process variability under different field conditions. Given the variability characteristics of a specific build-up or wash-off event, the theoretical scenarios help to infer the variability characteristics of the associated pollutant process that follows. Mathematical formulation of the theoretical scenarios enables the incorporation of variability characteristics of pollutant build-up and wash-off processes in stormwater quality models. The research study outcomes will contribute to the quantitative assessment of uncertainty as an integral part of the interpretation of stormwater quality modelling outcomes.

1. Introduction

Stormwater pollution is a significant issue in urban areas as stormwater runoff transports a range of pollutants to urban receiving water bodies leading to the deterioration of water quality. Therefore, mitigation of stormwater pollution is of importance in the context of safeguarding the urban ecosystem (De Martino et al., 2011; De Paola and Ranucci, 2012). In this regard, stormwater quality models are

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important tools employed for simulating the various pollutant processes, and provide essential knowledge for management decision making in relation to stormwater pollution mitigation. However, the decision making process is associated with uncertainty as a result of the uncertainty in the modelling outcomes (Loucks et al., 2005; Xu and Tung, 2008; Zoppou, 2001).

Uncertainty in modelling outcomes commonly arises from the uncertainty inherent to pollutant processes (e.g. build-up, wash-off), and uncertainty in process modelling. Process uncertainty is generated from the intrinsic variability of processes, which stems from the behaviour of particulates and temporal variations in particle-bound pollutant load and composition during stormwater pollutant processes (Haddad et al., 2013; Hvitved-Jacobsen et al., 2010; Viklander, 1998). Inaccurate conceptualisation and simplification of stormwater pollutant processes (e.g. process variability) result in modelling uncertainty (Liu et al., 2012). Zoppou (2001) noted the importance of taking this uncertainty into consideration when evaluating modelling outcomes in order to make informed decisions. As such, an uncertainty analysis that accounts for the overall uncertainty (process and modelling uncertainty) needs to be undertaken.

However, commonly used stormwater models such as Storm Water Management Model-SWMM (Huber and Dickinson, 1988) do not include uncertainty analysis. On the other hand, typical uncertainty analysis techniques used in urban stormwater quality modelling generally account only for uncertainty that results from sources such as model parameters, input and calibration data (Dotto et al., 2012). Additionally, past studies on uncertainty assessment of urban hydrological modelling have developed approaches to address some specific types of uncertainties such as the model bias uncertainty, which is primarily induced by input measurements and model structural deficiencies (Giudice et al., 2013; Honti et al., 2013). However, accounting for the process uncertainty is necessary as the impact of this uncertainty on model outcomes can neither be minimised nor eliminated due to its inherent nature. Specifically, the poor characterisation of the uncertainty sources in stormwater quality models limits the process uncertainty from being appropriately accounted for in the uncertainty analysis. As such, the importance of characterising the intrinsic process variability in the modelling process is recognised in past studies (Helton and Burmaster, 1996).

The objective of the current study was to characterise the variability in pollutant build-up and wash-off, and to develop a mathematical approach to assess process variability in relation to stormwater quality modelling. This investigation was based on past research findings that particle size fractions <150 μm and >150 μm during build-up and wash-off primarily influence process variability. Wijesiri et al. (2015a) reported that particles <150 μm and >150 μm exhibit characteristically different build-up patterns, namely, decreasing and increasing patterns, respectively, over the antecedent dry period. In effect, particulate composition (mixture of the amounts of particle size fractions <150 μm and >150 μm) in build-up at the end of the antecedent dry period is influenced by different combinations of the build-up patterns of the two particle size fractions.

On the other hand, according to Sartor and Boyd (1972), the form of the particulate wash-off pattern over the duration of a storm event is similar for different particle size ranges, while particle size influences the amount of washed-off particles. Consequently, different sized particles are found to follow an increasing pattern during wash-off. A study by Wijesiri et al. (2015b) further confirmed that the wash-off of particles <150 μm and >150 μm follow the same increasing pattern. Specifically, Wijesiri et al. (2015b) also noted that the wash-off load of the two particle size fractions vary proportionately with the build-up of the respective particle size fractions available at the beginning of a storm event. This means that the influence exerted by the particle size fractions <150 μm and >150 μm on particulate composition in wash-off load is significant, irrespective of the similarity in the wash-off patterns.

As such, how process variability stems from the temporal variations in particles <150 μm and >150 μm during pollutant build-up and wash-off is discussed in Wijesiri et al. (2015a) and Wijesiri et al. (2015b), respectively. Accordingly, this paper presents a scientifically robust approach underpinned by in-depth analysis, for incorporating process variability in pollutant build-up and wash-off in stormwater quality modelling predictions.

2. Materials and methods

2.1. Study sites

The primary consideration in site selection was to ensure that build-up and wash-off samples contain particulates of a wide range of sizes. Accordingly, eight road sites in two suburbs (Clearview Estate-Nerang and Benowa) were selected from Gold Coast, Queensland, Australia. The aerial and street views of the selected road sites are shown in Figs. S1, S2 and S3 in the Supplementary information.

Both suburbs are located within the Nerang River catchment, which is the largest waterway system in the Gold Coast region. The inland Clearview Estate-Nerang suburb is predominantly a residential area, while residential and commercial land uses can be identified in the Benowa suburb, which is closer to the coastline. Each road site was selected encompassing different traffic volumes. Relatively high traffic flow could be observed at road sites located at Benowa compared to those at Clearview Estate-Nerang. The surrounding urban form at Clearview Estate-Nerang is characterised by detached housing, together with a population density of 456.6 residents/km^2 and a household density of 402.6 households/km^2. The urban form at Benowa comprises of detached and town housing, waterfront properties, warehouses, workshops, school premises, together with a population density of 1173.4 residents/km^2 and a household density of 167.1 households/km^2 (ABS, 2011). All the selected road surfaces are asphalt paved, and those at Clearview Estate-Nerang are in good condition with a fair slope. The selected road sites at Benowa consist of mild slope and are in relatively poor condition.

2.2. Build-up and wash-off sample collection

Particulate build-up samples corresponding to nine antecedent dry periods (2, 4, 5, 7, 8, 10, 12, 19 and 24 days) were collected at each road site. The antecedent dry periods were selected based on the fact that particulate build-up occurs at a rapid rate immediately after a removal event such as a storm event, and subsequently asymptotes to an almost constant value at around nine days (Ball et al., 1998; Egodawatta and Goonetilleke, 2006). A wet and dry vacuum system, which was found to have a sample collection efficiency of 98% was used to collect the build-up samples. The vacuum system consisted of a portable vacuum cleaner incorporated with a water filtration unit (Delonghi Aqualand Model) and a water sprayer (60 L Swift Compact Sprayer). A 3 m^2 plot on each road surface was initially dry vacuumed, and the demarcated plot area was then moistened using the water sprayer before wet vacuuming. It was found in previous research studies (e.g. Gunawardana et al., 2012; Mahbub et al., 2011) that wet vacuuming specifically enhances the collection efficiency of fine particles.

Simulated rainfall was used to collect particulate wash-off samples from the study sites. It was necessary to select road sites where sufficiently large amount of particulate solids is available on the road surface prior to simulating rainfall. As such, Yarrimbah Drive from Clearview Estate-Nerang suburb and De Haviland Avenue from Benowa suburb were selected after analysing the particulate build-up at all eight road sites. A rainfall simulator, which was verified for its simulation performance of specific rainfall intensities, was used to simulate storm events with different intensities and durations at the selected road sites. The intensities simulated were 45, and 60 mm/h at Yarrimbah Drive, and 30 and 70 mm/h at De Haviland Avenue. Each storm event was simulated over a duration of 30 min, while particulate wash-off samples were