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Assessing uncertainty in stormwater quality modelling

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ABSTRACT

Designing effective stormwater pollution mitigation strategies is a challenge in urban stormwater management. This is primarily due to the limited reliability of catchment scale stormwater quality modelling tools. As such, assessing the uncertainty associated with the information generated by stormwater quality models is important for informed decision making. Quantitative assessment of build-up and wash-off process uncertainty, which arises from the variability associated with these processes, is a major concern as typical uncertainty assessment approaches do not adequately account for process uncertainty. The research study undertaken found that the variability of build-up and wash-off processes for different particle size ranges leads to processes uncertainty. After variability and resulting process uncertainties are accurately characterised, they can be incorporated into catchment stormwater quality predictions. Accounting of process uncertainty influences the uncertainty limits associated with predicted stormwater quality. The impact of build-up process uncertainty on stormwater quality predictions is greater than that of wash-off process uncertainty. Accordingly, decision making should facilitate the designing of mitigation strategies which specifically addresses variations in load and composition of pollutants accumulated during dry weather periods. Moreover, the study outcomes found that the influence of process uncertainty is different for stormwater quality predictions corresponding to storm events with different intensity, duration and runoff volume generated. These storm events were also found to be significantly different in terms of the Runoff-Catchment Area ratio. As such, the selection of storm events in the context of designing stormwater pollution mitigation strategies needs to take into consideration not only the storm event characteristics, but also the influence of process uncertainty on stormwater quality predictions.

1. Introduction

In urban areas, the transformation of natural environment into residential, commercial and industrial land use leads to the generation of pollutants ranging from particulate solids to toxic particle-bound heavy metals and hydrocarbons (Brown and Peake, 2006; Hvitved-Jacobsen et al., 2010; WWAP, 2015). These pollutants, which accumulate on urban impervious surfaces over dry weather periods are entrained in stormwater runoff during storm events. The urban water quality is degraded once polluted stormwater runoff is discharged into receiving waters (Makepeace et al., 1995; Zhao and Li, 2013). Stormwater pollution is therefore a major concern in urban water management. As such, effective stormwater pollution mitigation is necessary for improving stormwater quality. In this context, informed decision making plays an important role in the design of effective pollution mitigation strategies.

Information on catchment stormwater quality is essential for planning and management decision making. This knowledge (stormwater quality predictions) is commonly generated using stormwater quality models which incorporate mathematical replications of primary pollutant processes, namely, build-up and wash-off (WWAP, 2012; Xu and Tung, 2008). However, it has been highlighted in past studies (e.g. Freni et al., 2009a; Helton and Burmaster, 1996; Métadier and Bertrand-Krajewski, 2011 and Zoppou, 2001) that uncertainties primarily arising from process modelling itself and the variability in pollutant processes significantly influence the interpretation of stormwater quality predictions. Decision making without adequate knowledge of these uncertainties can lead to the design of ineffective stormwater pollution mitigation strategies (Hvitved-Jacobsen et al., 2010; Loucks et al., 2005; Obropta and Kardos, 2007).

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Stormwater quality modelling uncertainty, which arises from sources such as model structure, input and calibration data and model parameters, is generally understood. A number of techniques are available for assessing modelling uncertainty as summarised in Table 1. However, these techniques exhibit significant drawbacks such as the use of user defined likelihood measures in Generalized Likelihood Uncertainty Estimation (GLUE) and the role of prior knowledge in Bayesian techniques in uncertainty assessments.

On the other hand, how inherent process uncertainty stems from process variability is investigated only in a limited number of research studies. Wijesiri et al. (2016) confirmed that process uncertainty can be quantitatively incorporated in build-up and wash-off predictions, which in fact, as highlighted by Zoppou (2001), is essential for informed decision making.

The approach for assessing build-up and wash-off process uncertainty proposed by Wijesiri et al. (2016) is based on mathematical formulations which replicate the temporal variations of the build-up and wash-off loads of particles <150 μm and >150 μm. These temporal variations describe different behaviours to each other during build-up and wash-off, which were found to primarily influence process variability (Herngren et al., 2006; Wijesiri et al., 2015a,b). Therefore, the incorporation of process variability into build-up and wash-off process models can account for the different behaviour of particles of different size fractions, which also result in differences in their association with other pollutants, while undergoing build-up and wash-off. This approach has previously been undertaken using only small-plot scale field data obtained from road surfaces. There is a need to translate this approach to catchment-scale water quality predictions in order to demonstrate the practical application of the study outcomes and to support the interpretation of model outcomes.

The primary objective of the investigation described in this paper was to quantitatively assess process uncertainty in relation to catchment scale stormwater quality predictions focussing on road surfaces, as these are the primary pollutant source to urban stormwater runoff. Accordingly, the research study focused on: (1) the translation of small-plot scale particulate build-up and wash-off data into catchment scale stormwater quality predictions; and (2) the extension of the uncertainty assessment approach proposed by Wijesiri et al. (2016) for small-plot scale pollutant processes models to catchment stormwater quality predictions. The outcomes of this study are expected to facilitate the development of approaches for enhancing stormwater pollution mitigation strategies to improve urban stormwater quality.

2. Materials and methods

2.1. Study design

Accurate model development followed by satisfactory calibration and verification is critical for the accuracy of the modelling outcomes. However, the lack of adequate data sets for calibration often challenges the reliability of most modelling approaches (Bertrand-Krajewski, 2007). As such, Egodawatta (2007) recognised that a modelling approach that utilises field data on pollutant build-up and wash-off for generating necessary model parameters enables the accurate prediction of stormwater quality, without having to perform model calibration. Similarly, the modelling approach developed and the uncertainty assessment undertaken in this investigation also utilised small-plot scale field data collected from urban catchments.

2.2. Study catchments

Three catchments: Gumbeel, Birdlife Park and Highland Park were selected from Gold Coast, South East Queensland, Australia. Gumbeel and Birdlife Park are small catchments located within the larger Highland Park catchment. The field investigations on particulate build-up and wash-off were undertaken at selected road sites located within each catchment. The selection of road sites was based on the fact that roads constitute a significant component of urban impervious surfaces and contribute significant pollutant loads to stormwater runoff. Figs. S1–S3 in the Supplementary Information show the aerial views of the selected catchments and the locations of road sites.

All three catchments are predominantly residential. Gumbeel, which is 1.6 ha in extent, consists of duplex housing. The catchment impervious area due to road surfaces (ratio between area of road surfaces and total catchment land area) is 15%, and has a simple and short drainage network compared to the other two catchments. Birdlife Park (7.5 ha) consists of single detached housing, and road surfaces form 12% of the impervious area. The drainage network in Birdlife Park includes road gutters and side manholes. The largest of the three catchments with an area of 105.2 ha, Highland Park, has fractions of commercial and forestry land uses in addition to the primary residential land use with single detached housing. The road surfaces form 16% impervious area. The drainage network in Highland Park includes pipes and channels which are connected to Bunyip Brook tributary that runs across the catchment.

The catchment area and the impervious area were calculated using Google Earth Pro. The impervious area was assumed to be evenly distributed over the catchment. The details of the drainage network in each catchment were obtained from the maps provided by the Gold Coast City Council. The roads in the sampling sites were found to have slopes varying from 7.2 to 10.8% and texture depth varying from 0.66 to 0.92 mm. Detailed information regarding the characteristics of the sampling sites located within each catchment can be found in Wijesiri et al. (2015a,b).

2.3. Small-plot scale field sampling and laboratory analysis

Particulate build-up and wash-off sampling were undertaken on small road surface plots (3 m^2) using a portable wet vacuum system and a rainfall simulator. The use of the rainfall simulator was to simulate storm events with different intensities and durations, and also to avoid the constraints associated with sampling under natural storm events. The performance of both sampling tools was validated under field conditions similar to the road surfaces in the study sites prior to being used in the field experiments. The

Table 1
Commonly used techniques for assessing stormwater quality modelling uncertainty.

Technique	References
Generalized Likelihood Uncertainty Estimation (GLUE)	Beven and Binley (1992), Freni et al. (2008), Freni et al. (2009a)
Shuffled Complex Evolution Metropolis Algorithm (SCEM-UM)	Vrugt et al. (2003)
Multi-algorithm Genetically Adaptive Multi-objective method (AMALGAM)	Vrugt and Robinson (2007)
Classical Bayesian Approach based on Markov Chain Monte Carlo (MCMC) method and the Metropolis-Hastings Sampler	Beven (2009), Doherty (2003), Freni et al. (2009b)